CORPS OF ENGINEERS, U. S. ARMY

DESIGN OF FLEXIBLE AIRFIELD PAVEMENTS FOR MULTIPLE-WHEEL LANDING GEAR ASSEMBLIES

REPORT NO. 2

ANALYSIS OF EXISTING DATA

TECHNICAL MEMORANDUM NO. 3-349

PREPARED FOR

OFFICE OF THE CHIEF OF ENGINEERS

AIRFIELDS BRANCH

ENGINEERING DIVISION

MILITARY CONSTRUCTION

BY

WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

JUNE 1955

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PREFACE

The study reported herein was proposed by the consultants to the Flexible Pavement Branch, Waterways Experiment Station, in a conference held on 30-31 March 1953, and was authorized by the Office, Chief of Engineers, in Addendum No. 5 (fiscal year 1954) dated October 1953 to "Instructions and Outline for Multiple-wheel Studies," dated October 1948.

Engineers of the Flexible Pavement Branch who were actively engaged in directing and carrying out the analysis were Messrs. W. J. Turnbull, C. R. Foster, and R. G. Ahlvin.

CONTENTS

SUMMARY

This study was conducted for the purpose of re-evaluating the current, tentatively adopted methods for resolving the existing single-wheel design criteria for flexible airfield pavements into criteria for multiple-wheel assemblies. Results of tests on the first multiple-wheel test section indicated that the current method yields design criteria for pavement and base thicknesses that are slightly on the unconservative side.

All available data that might provide means of comparing the effects of single and multiple loadings were reviewed and a new analysis was made. Both stress and deflection effects were examined wherever possible.

A proposed alternate theoretical means of resolving well-established single-wheel design criteria to give valid multiple-wheel criteria was developed. This alternate method of resolution is based solely on equivalent deflections, and appears to give somewhat better results than the tentative method now in use. The method has the distinct advantage of being capable of extension to any assembly configuration without additional assumptions.

DESIGN OF FLEXIBLE AIRFIELD PAVEMENTS FOR MULTIPLE-WHEEL LANDING GEAR ASSEMBLIES

ANALYSIS OF EXISTING DATA

PART I: PURPOSE AND SCOPE OF THE STUDY

Purpose

1. The purpose of this study was to analyze all available data pertaining to the relative severity of the effects of single- and multiple-wheel loadings on flexible airfield pavements, and to determine: (a) whether or not the present tentative method of resolving single-wheel criteria into criteria for multiple assemblies is adequate; (b) means for obtaining better results if the present method is not adequate; and (c) what additional verification, if any, is needed for the present method of resolution or for a suggested alternate method.

Scope

2. The study was limited to an analysis of existing data and to theoretical developments necessary to verify the existing method of resolving single-wheel criteria into criteria for multiple-wheel assemblies or to formulate an alternate method. For this purpose, information and data from the following reports were used:

- a. Report of the development of B-29 design criteria (4).*
- b. Report of the second traffic tests at Stockton Airfield, California (3).
- c. CBR Symposium, ASCE (1).
- d. Report on stress distribution in a homogeneous clayey silt test section (5).

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* Numbers in parentheses refer to the bibliography.

e. Report on theoretical stresses induced by uniform circular loads (7).

f. Report on stress distribution in a homogeneous sand test section (8).

g. Report of the first multiple-wheel traffic test section (6).

PART II: PRESENT TENTATIVE METHOD OF RESOLUTION

3. The present tentative method of resolving single-wheel criteria for design of flexible airfield pavements into design criteria for multiple-wheel assemblies is explained in detail in the CBR Symposium (1). It was first proposed in somewhat less complete form in the B-29 report (4). This method assumes that at shallow depths each wheel of a multiple assembly has an individual effect on pavements and subgrades, while below some greater depth the entire assembly acts as a single load (see plate 1). Between these depths the wheel-load effects progress in an orderly manner from one to the other.

4. These concepts provide a basis for arriving at a single-wheel load which is considered, for design purposes, to produce effects on the subgrade equivalent to those produced by a multiple-wheel load. This equivalent single-wheel load can then be used with the well-validated single-wheel CBR design curves presented in the Engineering Manual (2) to arrive at designs for a multiple-wheel assembly.

5. Depths, above which one wheel of a multiple assembly is considered to act as a single load and below which the entire assembly can be considered as a larger single load, have been established from theoretical and empirical data (1), (4). These depths have been expressed in terms of dimensions of the assembly configuration. The sketch shown below will help clarify an explanation of these dimensions.

The least distance between adjacent contact areas is designated as "d." The depth above which one wheel of an assembly is considered as a single wheel has been empirically established as one-half of this distance, or $\frac{d}{2}$. The greatest distance (center to center) between any two wheels of an assembly is designated as "S." The depth below which the assembly load is considered to be a single load has been empirically established

as twice this distance, or "2S." Between these two extremes, equivalent single-wheel loads are determined from a straight-line relation on a log-log plot. Plate 2 includes examples of this type of development for 150,000-lb assembly loads. In the case of the dual assembly, for instance, the load on one wheel of the assembly (75,000 lb) is the critical load for base and pavement thicknesses less than 12.6 in. The entire assembly load (considered as a single-wheel load) is critical for thicknesses greater than 112 in. Between these two points (75,000 lb at 12.6 in. and 150,000 lb at 112 in.) equivalent single-wheel loads are represented by the straight line shown on plate 2.

PART III: SUMMARY OF PERTINENT DATA

6. At the time the present tentative method of resolving single-wheel design criteria into criteria for multiple-wheel assemblies was formulated (August 1945), only a very limited amount of pertinent data was available. Since that time a number of investigations have produced directly comparable data for single- and multiple-type loadings, i.e., stress and deflection data which can be compared for single and multiple loadings. In one instance, that of the multiple-wheel test section tested in 1949 and 1950 at the Waterways Experiment Station, simulated aircraft traffic was applied to the test section with multiple-wheel gear. The results of these accelerated traffic tests indicated that the design curves developed using the present method of resolution give values which are slightly on the unconservative side. The data which provided a basis for the current study are described in the following paragraphs.

Data from Report on Certain Requirements for Flexible Pavement Design for B-29 Planes (4)

7. The B-29 report, in addition to developing the present tentative method of determining criteria for multiple-wheel landing gear assemblies, presents the results of "Flexible Pavement Tests, Marietta, Georgia." The Marietta tests provided stress and deflection measurements beneath B-24 single and B-29 dual wheels for a range of loads on four thicknesses of pavement and base overlying a weak subgrade. Data from tables 3 and 10 of the B-29 report were used in the current analysis, and plates 3 and 4 are taken directly from the B-29 report.

Data from Accelerated Traffic Test at Stockton Airfield (Stockton Test No. 2) (3)

8. The second Stockton test section included 18 items of various thicknesses divided generally into strong, medium, and weak subgrade

groups. Comparable single- and multiple-wheel stress and deflection data are available for all these items. While the testing at Stockton No. 2 included accelerated traffic tests using single loads, no traffic with multiple assemblies was applied; therefore, no equivalent results with traffic are reported. However, rather complete data comparing the effects on stresses and deflections produced by standing loads of single and multiple assemblies are included. The data pertinent to the analysis reported herein are shown in the Stockton report as exhibits I-9 through I-12 of appendix D, exhibits I-2 through I-19 of appendix C, and exhibits I-40 through I-44 of appendix F. Plots of vertical stress versus depth based on these data are shown on plate 5.

Design Curves for Very Heavy Multiple-wheel Assemblies, CBR Symposium, 1950 (1)

9. This article includes the data presented in the B-29 report and is included here because it extends the multiple-wheel developments a little further than does the presentation in that report. Plates 1 and 2 which are taken from the CBR Symposium portray the concepts that formed the basis of this method of resolution and illustrate the method.

Data from Investigation of Stress Distribution in a Homogeneous Clayey Silt Test Section (5)

10. The Waterways Experiment Station is currently studying the distribution of stresses and deflections in soil masses in connection with a long-range investigation aimed at the development of more rational methods of design of flexible pavements. Thus far, two homogeneous test sections have been constructed and testing thereon completed. The results of tests on the first of these, the clayey silt test section, include stresses and deflections measured in a homogeneous soil mass beneath static, single and dual, uniform circular loads. The single loads were of 1000-sq-in. circular area, while the dual loads consisted of two 500-sq-in. circular areas. Load intensities

of 15, 30, 45, and 60 psi were applied through the loading plates, and measurements were made at various offsets and depths such that stress and deflection versus offset curves could be developed for 1-, 2-, 3-, 4-, and 5-ft depths. Dual spacings of 3, 4.5, 6, and 7.5 ft were used. Deflection data used in the current analysis were extracted from plates 103 through 107 of the clayey-silt test section report and are shown on plate 6 herein. Plates 7 and 8 herein, which were taken directly from that report, are typical of normal and shear stress data presented in the report.

Theoretical Stresses Induced by Uniform Circular Loads (7)

11. The report on theoretical developments in connection with the stress distribution studies presents formulas developed from work done by A. E. H. Love (9) in 1929 that can be used to compute the stresses and deflections in a semi-infinite, homogeneous, elastic mass subjected to a uniform circular load. Stresses and deflections computed from these formulas are used in this analysis. The theoretical deflections on plate 9 were computed in this manner.

Data from Investigation of Stress Distribution in a Homogeneous Sand Test Section (8)

12. The results of tests on the homogeneous sand test section have recently been published. They include stresses and deflections measured in a homogeneous mass of dry sand beneath static, single and dual, uniform circular loads. Three plate sizes, 250, 500, and 1000 sq in., were used for both single and dual loadings. Intensities of 15, 30, and 60 psi were applied and dual spacings were included as shown in the following table.

Plate Size, sq in.	Dual Spacing, ft
250	2.5
500	3.0
500	6.0
1000	4.5

Measurements were made at sufficient points in the mass so that stress and deflection versus offset curves could be developed for 0.5-, 1-, 2-, 3-, 4-, and 5-ft depths. Pertinent data were used in preparing plates 10 and 11. Plates 12 and 13 were taken directly from the report on the sand test section; maximum deflections from these measurements, which were used in the multiple-wheel analysis, are shown in table 1.

Data from Multiple-wheel Test Section with Lean-clay Subgrade (6)

13. A test section was constructed and tested at the Waterways Experiment Station to establish the validity of the present tentative method of developing design criteria for multiple-wheel landing gear assemblies on flexible airfield pavements. This test section was built of crushed limestone on a processed lean-clay subgrade and was surfaced with a 3-in. layer of asphaltic concrete. Two parallel lanes were included, each divided into three parts. The thickness of the central section of one lane was determined from the tentatively established criteria for a B-29 assembly loading. The end sections were, respectively, a 30 per cent underdesign and a 30 per cent overdesign in terms of thickness. The second lane included, similarly, a 30 per cent underdesign, correct design, and a 30 per cent overdesign for a B-36 assembly. These lanes were subjected first to traffic with the assemblies for which they were designed and subsequently to heavier loadings.

14. It was concluded from this study that the present tentative method of deriving multiple-wheel design curves gives criteria slightly on the unconservative side. Results of the study that are pertinent to this analysis are included as plates 14 and 15 which are modifications of plates in the "multiple-wheel report."

PART IV: ANALYSIS

15. The present method of resolution of single- into multiple-wheel design criteria was based on a compromise between stresses and deflections used as a basis for arriving at a single-wheel load equivalent for design purposes to the multiple-wheel load. By this method depths were determined above which individual wheels act independently and below which multiple-wheel assemblies act as a unit. Between these two points a straight-line relation on a log-log plot was accepted as a simple yet satisfactory representation of the variation in effective single-wheel load. The reanalysis is made on the basis of both deflection and stress using the theory of elasticity to compute equivalent single-wheel loads rather than the two established points and an approximate geometric relation for intermediate points. Curves developed on the basis of deflection and stress are compared with available traffic behavior data.

Analysis Based on Deflection

Original analysis

16. The original analysis of deflection data considered that strain was an important criterion and that the critical strain is represented by the rate of change of deflection with offset along the deflection profile. It also considered that the effects produced by a dual loading could be produced by a single load with the same pressure intensity having a gross magnitude between that of one and both wheels of the dual. These considerations are reasonable and remain unquestioned by any reanalysis.

17. Although the slope of deflection profiles was accepted as an important criterion, data were not adequate to develop such profiles at the time of the original analysis. It was therefore assumed that the maximum deflection was representative of the critical slope and that the maximum deflection for a dual assembly occurred beneath the center of one wheel of the assembly. With the additional data now available, deflection profiles can be developed and the magnitudes and positions of maximum deflections beneath multiple-wheel assemblies can be reasonably determined.

18. The crucial element of the original development as regards deflection data is shown in the plots on plate 3. Deflection-depth relations were empirically shown to be straight-line relations on log-log plots. The lines representing these relations for a dual assembly, one wheel of the assembly, and a single wheel of the same gross load as the assembly, were then plotted on a single log-log plot (see plate 3). These lines were extended well beyond the range of available data such that the dual-load line intersected each of the other lines. The intersection with the smaller single-wheel-load line gave a depth above which the dual load was considered to have the same effect as the single, while the intersection with the larger single-wheel-load line gave a depth below which the dual assembly was considered to have the same effect as the larger single load.

19. Both theoretical data and later test data show that the relation between thickness and deflection is not well represented by a straight line on a log-log plot. Plate 10, which was developed from later data, shows this quite clearly. Straight lines can be used to represent the true relation for narrow ranges in depth, and this was done for the analysis discussed in the previous paragraph, but even small extrapolations of these straight lines gave undesirable errors. Both theoretical and later test data also showed that for commonly used spacings the second wheel of a dual assembly contributes an appreciable portion of the maximum deflection even for depths near the surface. This is shown by the single-wheel curves for deflection versus offset on plates 6, 9, and 11 where it can be seen that appreciable deflections are produced by a single wheel at offsets commensurate with reasonable dual spacings. One wheel cannot, therefore, be considered to act independently even at very shallow depths. The over-all effect of these discrepancies is not large and the design curves developed by the current methods of resolution are only slightly unconservative.

Multiple-wheel test section

20. The results of traffic-testing with multiple-wheel assemblies are indicated on plate 14. The first "multiple-wheel report" also included an analysis based on deflection, the results of which are shown

on plate 15. Both of the analyses in the multiple-wheel test section report tend to show that the design criteria in present use give designs that are slightly unconservative.

New method of resolution

21. Since the present tentative method of resolving single-wheel criteria to criteria for multiple-wheel assemblies appeared to be somewhat inadequate, development of an alternate, better method was considered desirable. The reanalysis of stress data described later in paragraphs 35 through 38, indicated no variance with the earlier concepts on which the present method was based. However, the reanalysis of deflection data including analysis of more recent data showed that better limiting assumptions can now be made which will give somewhat more realistic results. A new method has therefore been developed which is considered to give criteria consistent with both stress and deflection data and to be in better agreement with traffic test results.

22. Failure is produced in a pavement system by a movement or dislocation of material. This movement is manifested as strain or deflection. It is reasonable, therefore, to look to strain or deflection as a criterion of failure. Little or no strain data are available, but as was pointed out in the original analysis and is re-emphasized in this analysis, it is reasonable to accept the slope (rate of change) of a deflection versus offset curve as indicative of the critical strain.

23. Thus, if it can be shown that a multiple-wheel load which produces a maximum deflection equal to that of a single-wheel load yields deflection versus offset curves at various depths whose slopes are less than those for the single load at equal depths, it may be concluded that the multiple-wheel assembly is creating no more severe strains than the single wheel. Pertinent data are available from the stress distribution studies (5), (7), (8). Plate 9 (theoretical developments) and plates 6 and 11 (results of tests on the homogeneous clayey-silt and sand test sections) show the relation between deflection versus offset curves at equal depths for single and dual assemblies. Without exception the slopes of the deflection versus offset curves for the single loads are equal to or steeper than those for the dual loads at equal depths.

24. From this analysis it appears that a single-wheel load which yields the same maximum deflection as a multiple-wheel load will produce equal or more severe strains in the subgrade or base than will the multiple-wheel load. The single load may, therefore, be considered equivalent to the multiple-wheel load for purposes of design, and it is proposed that the existing well-validated single-wheel curves and this equivalent single-wheel load be used to develop designs for multiple-wheel assemblies.

25. The slopes of some of the single-wheel deflection profiles in plates 6, 9, and 11 are appreciably greater than their dual-wheel counterparts. Therefore, for design purposes, it might be considered that assuming the single-wheel loads equivalent to their dual counterparts would introduce too much conservatism. As will be shown later, however, the proposed method gives design criteria only a little more conservative than that currently used, which has been shown to be slightly on the unconservative side.

26. Comparison of the theoretical curves of plate 9 with the test data curves of plates 6 and 11 shows that the theoretical curves are similar in general form to those derived from test data, and that for all but the shallowest depths the similarity of the curves is quite close. At the shallow depths discrepancies occur for the wide offsets, but at these depths the maximum deflections for a multiple assembly are almost entirely the result of the load on one wheel. For this reason discrepancies at wide offsets can have only a slight effect, and it is therefore considered that theoretical deflections can be used in arriving at the relation between single- and multiple-wheel assembly loads.

Determination of equivalent single-wheel load

27. Each wheel of a multiple-wheel assembly contributes a part of the maximum deflection occurring at any depth beneath such an assembly. Curves of deflection versus offset for various depths for a single wheel can be determined theoretically. Reference (5) includes a set of theoretical curves from which deflections at any offset and depth can be interpolated. Reference (7) describes methods and gives formulas that

permit the direct computation of deflections at any offset and depth. From the single-wheel curves, curves of deflection versus offset can be developed for multiple-wheel assemblies by use of the principle of superposition. Using single- and multiple-wheel curves of this type the maximum deflections at a given depth beneath single- and multiple-wheel assemblies can be determined. By equating these deflections a relation between multiple-wheel and equivalent single-wheel loads can be established. In equating these deflections the contact area of the single wheel is taken to be constant and the same as that of one wheel of the multiple assembly. By determination of the equivalent single-wheel load for a number of depths throughout the pertinent depth range, a relation between depth and equivalent single-wheel load can be established. This relation can then be used to resolve the established single-wheel design criteria into criteria for multiple assemblies. An example of the determination of equivalent single-wheel load is given in appendix A.

28. Design curves developed by use of this method were produced for capacity operation and are shown by dotted lines on plates 14 through 22, inclusive, for the various assemblies represented in these figures. For comparison, the corresponding curves, based on current criteria, are shown on these plates by solid lines.

Validation of new method of resolution

29. Analyses similar to those used in processing the data from the multiple-wheel test section (6) have been made wherever data were adequate. These consist of developing curves of single-wheel load versus maximum deflection from test data then using these curves with the maximum deflections occurring beneath multiple-wheel loads to determine an equivalent single-wheel load. By using this equivalent single-wheel load, single-wheel CBR design curves can be used to arrive at the required thickness for the multiple-wheel load.

30. Multiple-wheel test section. Design curves developed based on the proposed method are plotted on plates 14 and 15 along with the present design curves. In addition to these curves plate 14 shows points indicating test section behavior under traffic of 2000 coverages. Plate 15,

in addition to the curves, shows points that represent design thicknesses based on equivalent single-wheel loads determined as stated in the previous paragraph. Plate 14 shows the new curves to be in better agreement with the plotted points than are the curves developed using the present method of resolution. On plate 15 only the 0 coverage points are completely valid and these show the new curves to be a better correlation than the old. The points for larger numbers of coverages are not based on completely comparable deflection data since single-wheel deflections were measured only at 0 coverages.

31. Marietta test section. No traffic data were collected during the Marietta tests, but sufficient data on deflection under standing loads, both single and dual, are available for an analysis based on equivalent single-wheel loads. Such analysis was made in the same way as for the multiple-wheel test section data. The results are presented on plate 16 together with design curves determined from both the present and proposed methods of developing criteria.

32. Stockton test section No. 2. No traffic data for multiple-wheel assemblies were collected during the Stockton tests, but a considerable amount of deflection data was assembled. Accordingly, an analysis was made based on equivalent single-wheel load as was done for the Marietta data. Results are presented on plate 17 along with present and proposed design curves. Here, again, as with the multiple-wheel test section (paragraph 30), some of the equivalent deflection data (single-multiple) are not for comparable numbers of coverages. Only 0 coverage multiple-wheel deflections were measured and 0 coverage single-wheel deflections were not reported in every case.

33. Stress distribution test sections. Deflection data are available from both the clayey silt and sand test sections used in the stress distribution investigation. These data have also been analyzed on the basis of equivalent single-wheel loads as was done with the Stockton and Marietta data. Results are shown on plates 18 through 21. Since no data for a single load of the same contact area as one of the duals were available for the clayey silt, a conversion of the available single-load data was made, based on theoretical concepts.

34. Results. The service behavior analysis (plate 14) shows better agreement between the plotted points and the design curves based on the proposed method of resolution of single- to multiple-wheel criteria than between the points and curves based on the present method. This provides the strongest validation of the proposed method. The various other analyses tend to support this validation. For these latter, it might be argued that the criteria and validation analyses have something of the same basis. On the other hand, no better means of analysis was found and without it the bulk of available data could not be compared.

Analysis Based on Stress

Original analysis

35. The analysis of theoretical stress data as presented in the B-29 report (4) remains unchanged and is quite valid. Plate 4 presents this analysis together with vertical stress measurements from the Marietta tests (4). It indicates that, at depths less than about 16 to 20 in., the effect of a B-29 dual assembly on the subgrade is the same as or less severe than the effect of a single wheel equivalent to one wheel of the dual. The analysis further indicates that the B-29 dual assembly produces much the same amount of stress below a depth of about 75 to 80 in. as does a single wheel having the same gross load. Since these relations are largely theoretical, the depths can be considered in terms of radii of the loaded area to give evidence in substantiation of the d/2 and 2S method of resolution (see paragraph 5).

Later pertinent data

36. Additional evidence has become available that shows the distribution of stresses beneath wheel loads or simulated wheel loads to be much as indicated by computations based on the theory of elasticity (Boussinesq theory). Plates 5, 7, 8, 12, and 13 present test results that bear out this conclusion. Plate 5 was prepared from the Stockton No. 2 test data and from computations using the methods presented in the stress distribution report on theoretical developments (7). Plates 7 and 8 were taken directly from the clayey silt test section report (5).

Plates 12 and 13 have been prepared for use in the report on the sand test section studies (8).

Reanalysis

37. The data just presented serve to prove that it is valid to use theoretical stresses in lieu of actual stresses for analysis. Such theoretical stresses formed most of the basis for the original analysis insofar as it was based on stresses. Since this reanalysis only strengthens the original analysis and since the original analysis led to inadequate results, the correlations serve to further prove the inadequacy of normal and shearing stress as a basis for relating the effects of single and multiple loadings.

Equivalent single-wheel load based on maximum shear stress

38. In the current studies, maximum shear stresses were also tried as a basis for developing multiple-wheel design criteria. By using the procedures outlined in paragraph 27 a method of resolving single-wheel criteria into multiple-wheel criteria, similar to the proposed method but using shear stress instead of deflection, was evolved. From this design curves for the B-29 were developed. In general, these curves are even less conservative than those using the present method of resolution (see plate 22). Therefore the method is not considered worthy of further pursuance.

Comparison of Design Criteria

39. In order to show the effect on designs of the use of the present, proposed, and shear-stress methods of resolution, curves on both semilog and log-log plots have been developed for the B-29 airplane. These are shown on plate 22. Comparison reveals that the proposed method for developing multiple-wheel design criteria gives results roughly equivalent to, yet somewhat more conservative than, the present method. The shear-stress method yields the least conservative criteria of the three.

Advantage of the Proposed Method of Resolution

40. If the relation between single and dual computed deflections is accepted as adequately representing that for actual deflections, the proposed method provides a rational relation between multiple- and equivalent single-wheel loads. Thus, any new configuration of landing gear wheels can be handled as readily as those now existing.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

41. Based on the analysis herein pertaining to the development of criteria for designing flexible airfield pavements for multiple-wheel landing gear assemblies, the following conclusions appear warranted:

- a. The present tentative method of resolving single-wheel into miltiple-wheel designs gives criteria slightly on the unconservative side.
- b. Neither vertical stress nor maximum shear stress provides an adequate basis for relating the effects of single- and multiple-wheel assemblies.
- c. Strains, which are in effect the slopes of deflection versus offset curves, provide the best basis for arriving at single-wheel loads that are equivalent, for design purposes, to multiple-wheel loads.
- d. These strains are adequately represented in relative magnitude by theoretical maximum deflections, and satisfactory design criteria for multiple-wheel assemblies can be developed from established single-wheel criteria on the basis of equal maximum deflections.

Recommendations

42. Based on knowledge gained from the analysis or reanalysis of available data pertinent to design of flexible airfield pavements for multiple-wheel assemblies, the following actions are recommended:

- a. Adoption of the method of resolution proposed herein as the basis for developing design curves for multiple-wheel landing gear assemblies from well-validated single-wheel design curves.
- b. Construction and testing of a second test section involving greater design thicknesses to provide data for checking the validity of design criteria for weaker subgrades. In this respect it appears that unusual wheel configurations need not be used. It is also recommended that only a surface treatment be used on the test section in order to eliminate the effects of temperature, and perhaps other factors, on pavement strength.

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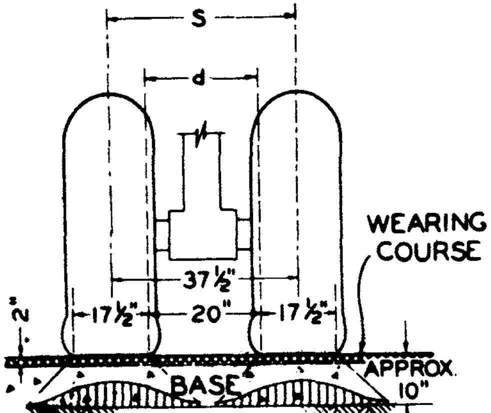
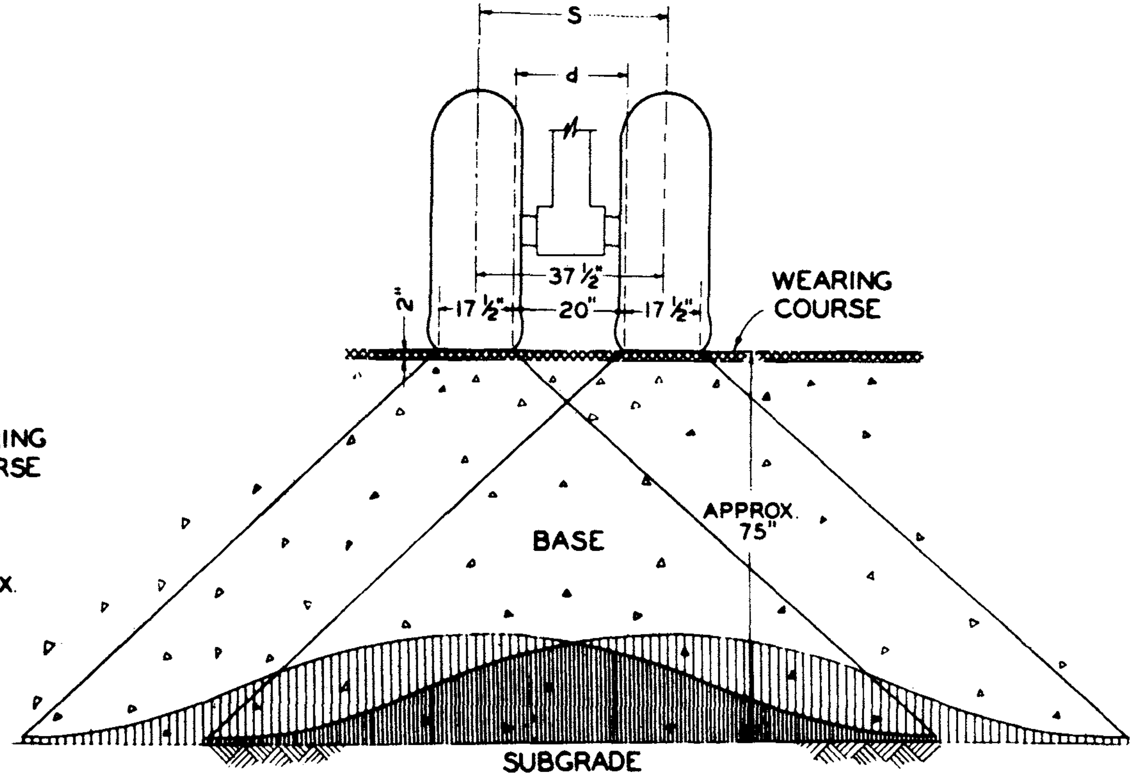
Table 1

Maximum Deflections Homogeneous Sand Test Section

Plate Size sq in.	Spacing ft	Surface Load Intensity psi	Maximum Deflection in Inches for Depth 0.5 ft	1 ft	2 ft	3 ft	4 ft	5 ft
250	Single	15	.0165	.0081	.0024	.0019	.0009	.0015
		30	.0210	.0126	.0048	.0030	.0012	.0048
		60	.0420	.0276	.0120	.0060	.0036	.0024
	2.5	15	.0225	.0096	.0053	.0021	.0023	.0015
		30	.0240	.0168	.0072	.0042	.0045	.0018
		60	.0480	.0312	.0144	.0084	.0048	.0036
500	Single	15	.0183	.0123	.0051	.0030	.0024	.0024
		30	.0252	.0186	.0102	.0063	.0030	.0018
		60	.0516	.0420	.0216	.0120	.0060	.0036
	3.0	15	.0318	.0176	.0069	.0039	.0030	.0024
		30	.0324	.0216	.0132	.0084	.0048	.0036
		60	.0600	.0468	.0276	.0168	.0108	.0096
1000	Single	15	.0263	.0180	.0114	.0050	.0038	.0024
		30	.0357	.0268	.0150	.0099	.0060	.0054
		60	.0751	.0595	.0320	.0210	.0144	.0096
	4.5	15	.0330	.0228	.0081	.0069	.0051	.0033
		30	.0390	.0324	.0192	.0108	.0102	.0066
		60	.0816	.0720	.0456	.0300	.0240	.0204



SHALLOW BASE
FIG A

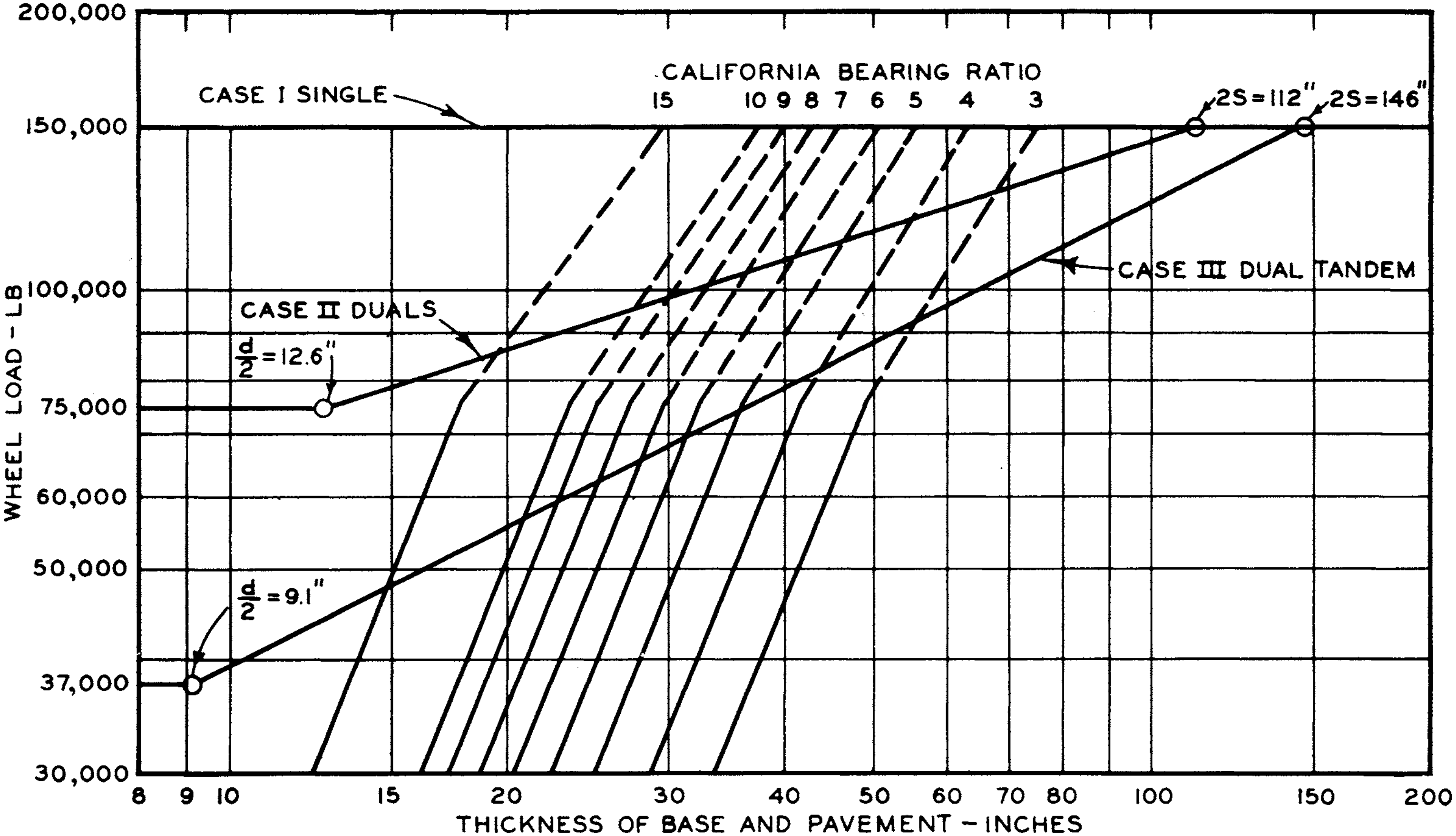


DEEP BASE
FIG B

PLATE TAKEN DIRECTLY
FROM CBR SYMPOSIUM

SCHEMATIC DIAGRAM OF B - 29 DUAL WHEEL ASSEMBLY

082 453 B



NOTE: TAKEN DIRECTLY FROM CBR SYMPOSIUM.

TENTATIVE METHOD OF COMPARING THICKNESS REQUIREMENTS FOR VARIOUS WHEEL LOAD ASSEMBLIES

08245 3D

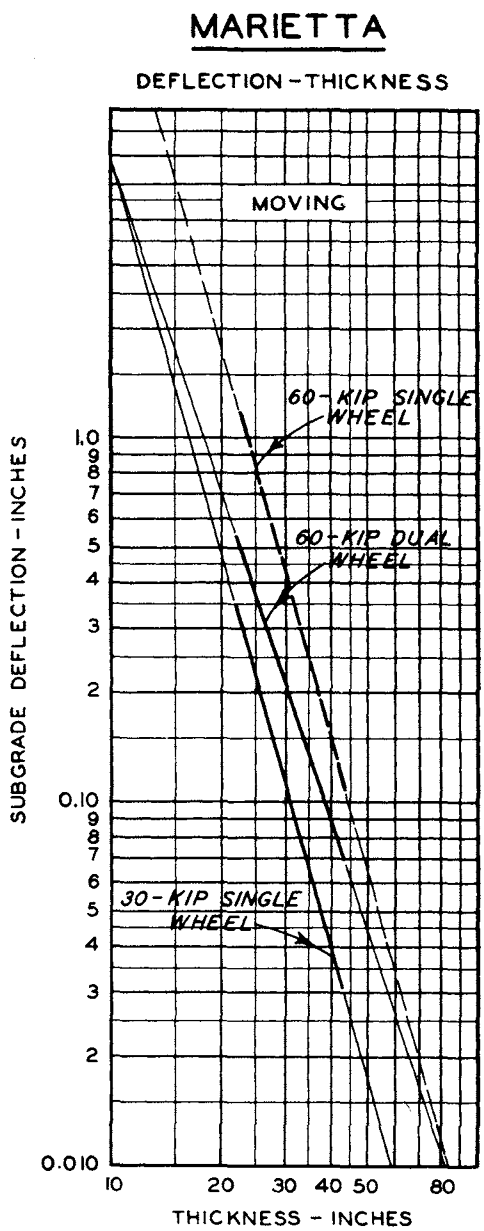


FIGURE A

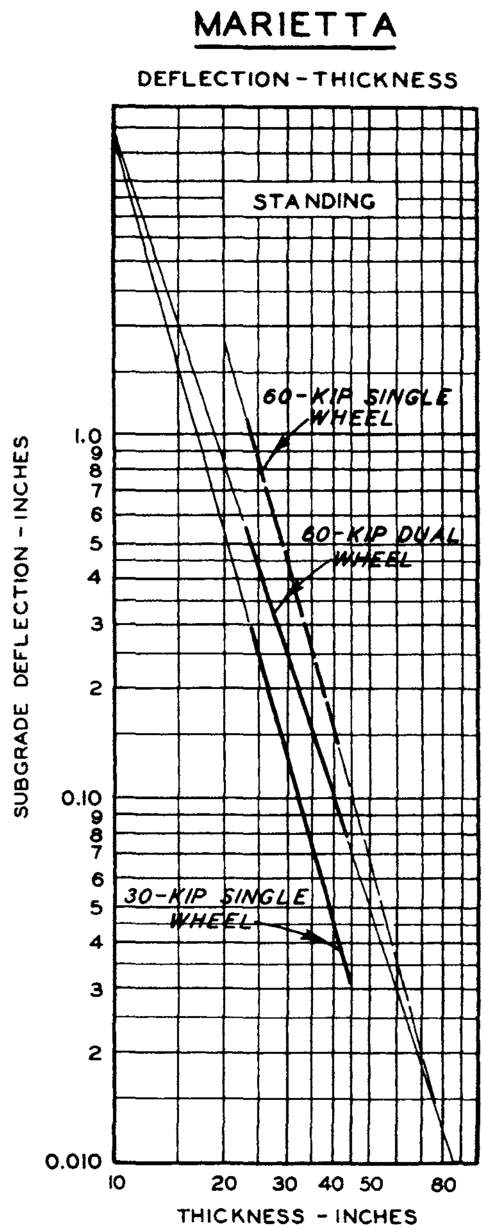


FIGURE B

TAKEN DIRECTLY FROM REPORT ON
FLEXIBLE PAVEMENT DESIGN FOR B-29 PLANES

SUBGRADE DEFLECTIONS
SINGLE VS DUAL WHEELS

090153 A

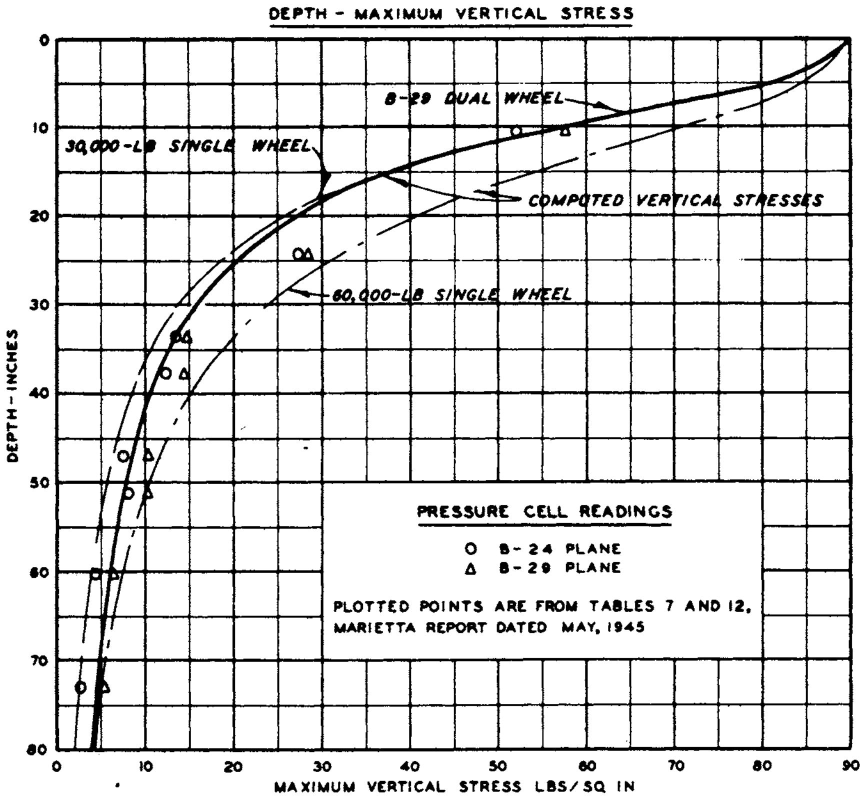


FIGURE A

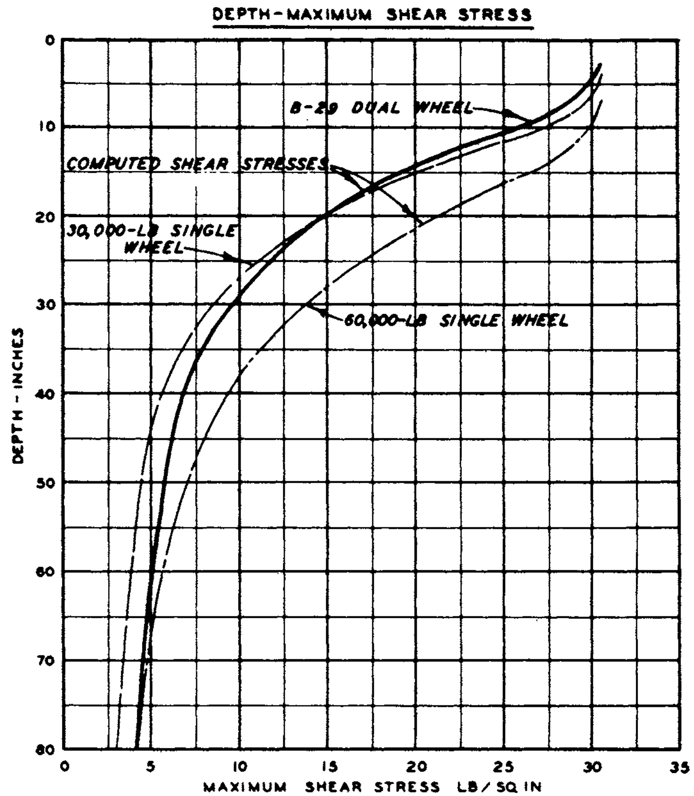


FIGURE B

TYPE OF WHEEL	LOAD PER TIRE LB	MAJOR AXIS - IN.	MINOR AXIS - IN.	TOTAL CONTACT AREA SQ IN.	CONTACT PRESSURE LB/SQ IN.	DUALS C-C IN.
SINGLE (B-24)	30,000	27.12	15.73	335	89.55	—
DUAL (B-29)	30,000	27.12	15.73	670	89.55	37.0
SINGLE	60,000	38.35	22.24	670	89.55	—

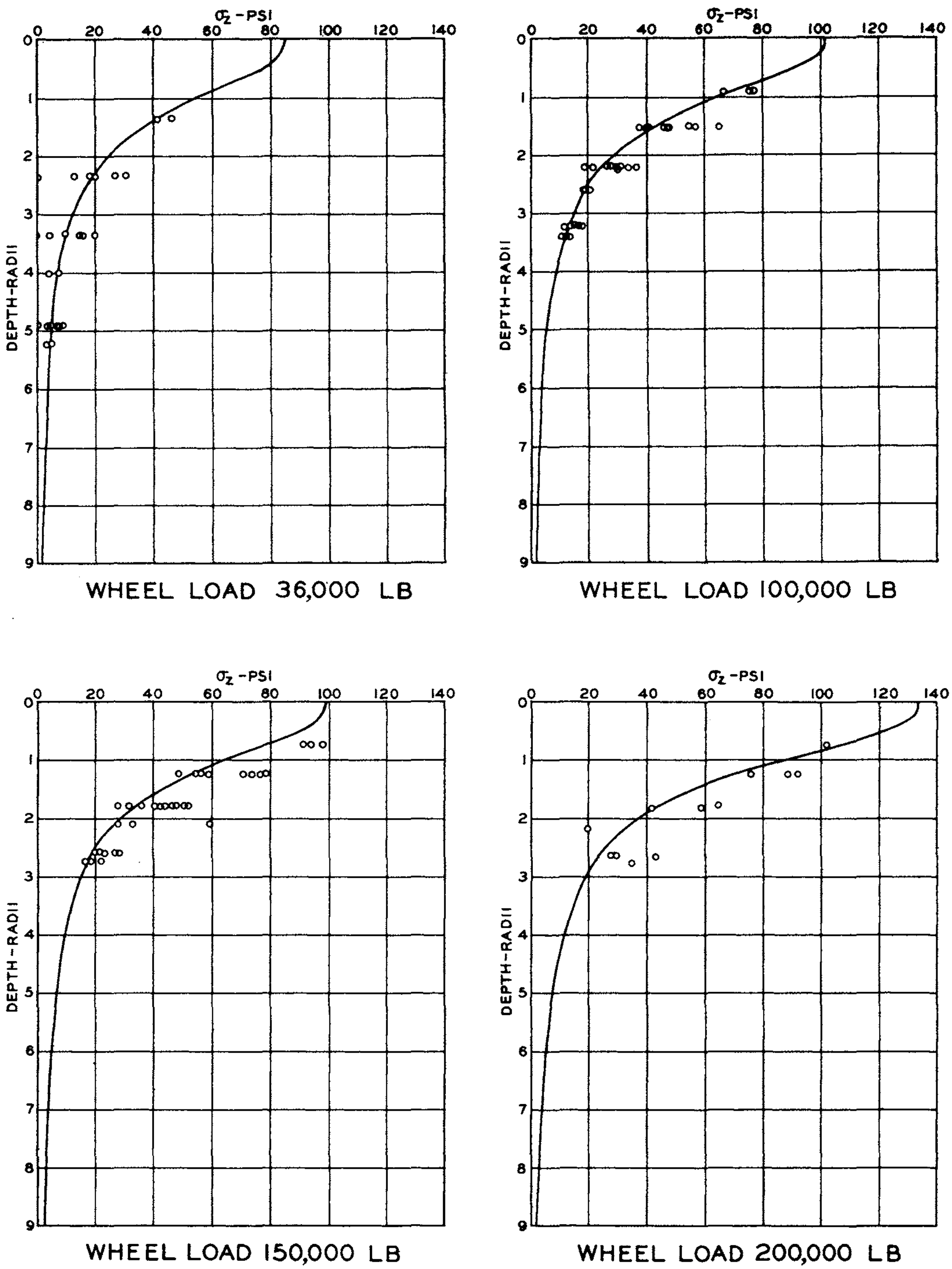
ELLIPTICAL CONTACT AREAS
CONCENTRATION FACTOR (N) = 3

NOTE:
1. COMPUTATIONS OF STRESSES WERE MADE USING NEWMARK'S STRESS CHARTS AND OTHER GENERALLY ACCEPTED STRESS FORMULAE.

TAKEN DIRECTLY FROM REPORT ON
FLEXIBLE PAVEMENT DESIGN FOR B-29 PLANES

VERTICAL AND SHEAR STRESSES

062453C



LEGEND

——— THEORY (BOUSSINESQ)

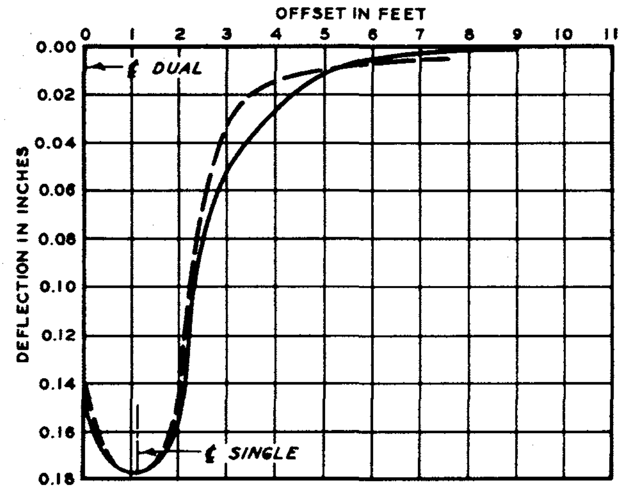
o POINTS FROM STOCKTON TEST 2

STRESS VS DEPTH

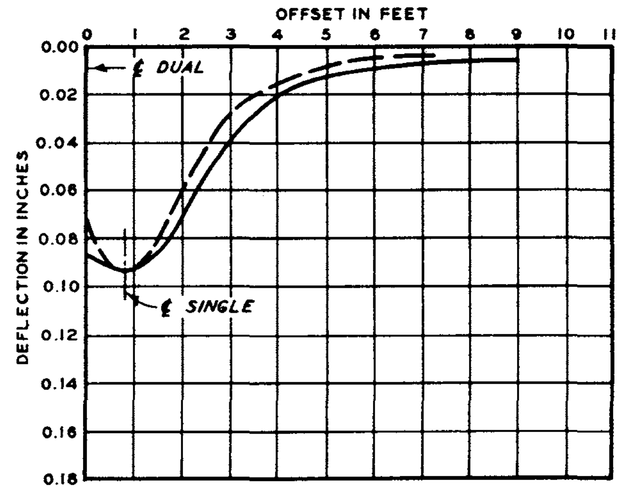
σ_z AT 0 OFFSET

SINGLE LOADS

082753-H

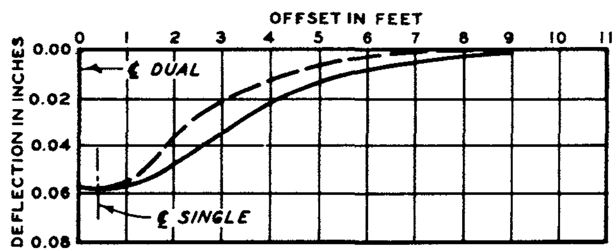


1.0-FOOT DEPTH



2.0-FOOT DEPTH

NOTE: 500-SQ-IN. PLATE, 3.0-FT DUAL SPACING.
SINGLE LOAD DEFLECTIONS WERE INCREASED BY RATIO TO MAKE MAXIMUM DEFLECTIONS FOR SINGLE AND DUAL LOADINGS EQUAL.
500-SQ-IN. SINGLE LOAD DEFLECTIONS WERE OBTAINED AT HOMOLOGOUS POINTS FROM 1000-SQ-IN. SINGLE LOAD DATA.
DEFLECTIONS WERE AVERAGED FROM THOSE PRODUCED BY 15-, 30-, 45- AND 60-PSI SURFACE LOAD INTENSITIES.



3.0-FOOT DEPTH

LEGEND

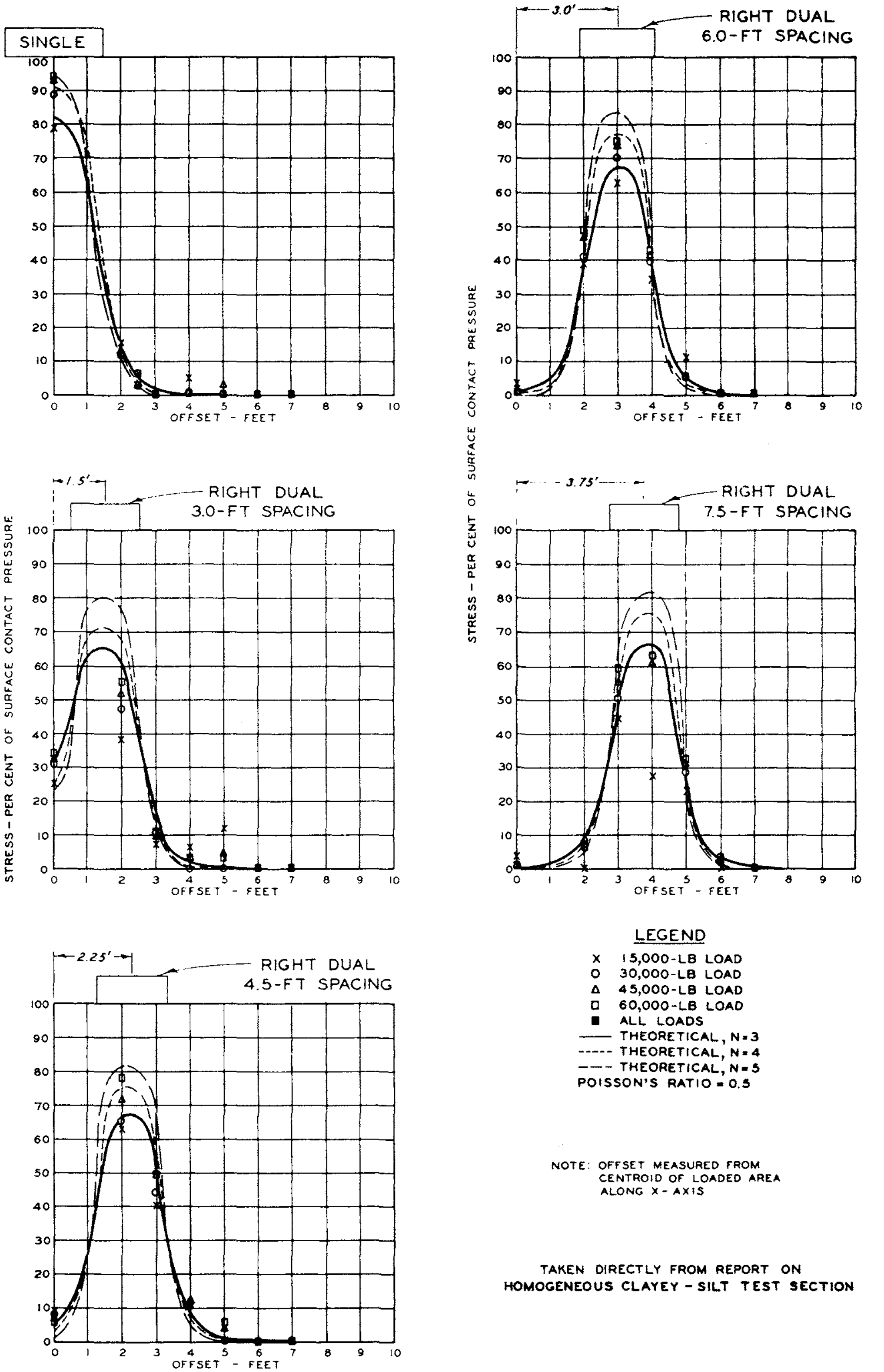
——— DUAL LOAD DEFLECTIONS
— — — SINGLE LOAD DEFLECTIONS

COMPARISON OF SINGLE AND DUAL DEFLECTION PROFILES

TEST DATA

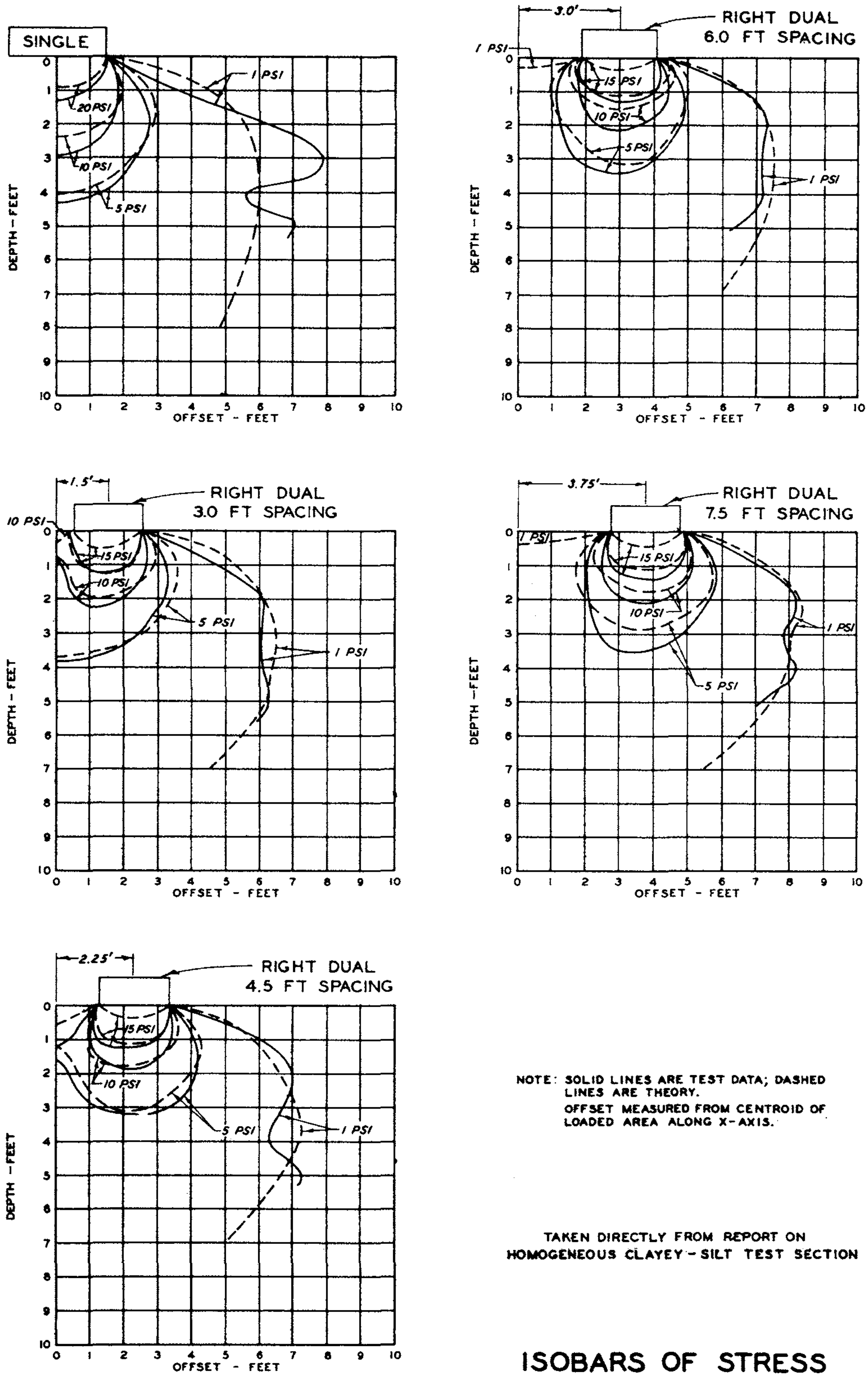
CLAYEY-SILT TEST SECTION

082753C



STRESS VS OFFSET DISTANCE
σ_z AT 1-FT DEPTH

090153 B

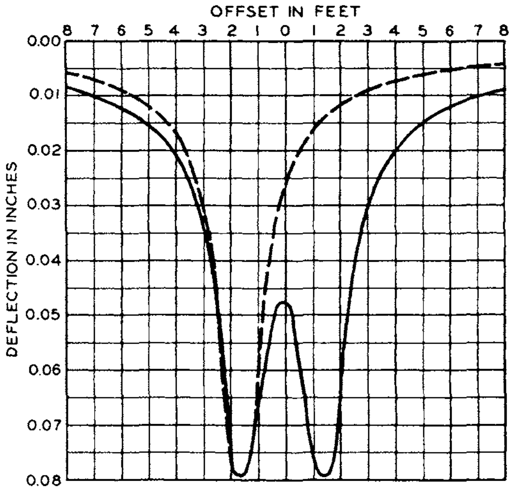


NOTE: SOLID LINES ARE TEST DATA; DASHED LINES ARE THEORY.
OFFSET MEASURED FROM CENTROID OF LOADED AREA ALONG X-AXIS.

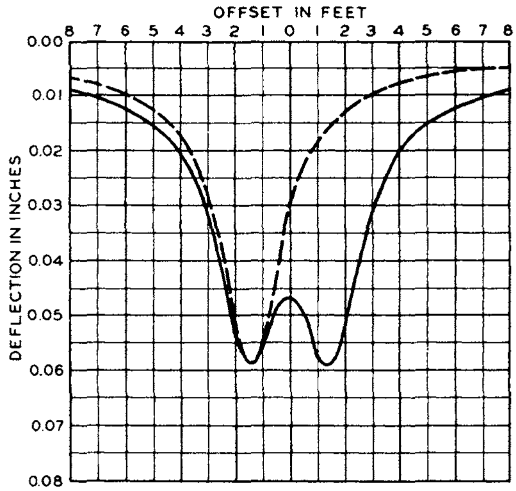
TAKEN DIRECTLY FROM REPORT ON HOMOGENEOUS CLAYEY-SILT TEST SECTION

ISOBARS OF STRESS
MAXIMUM SHEARING STRESS-τ_{MAX}
60,000-LB LOAD

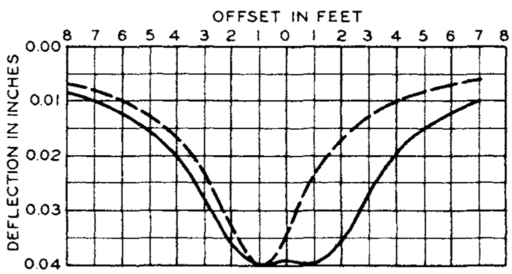
090153C



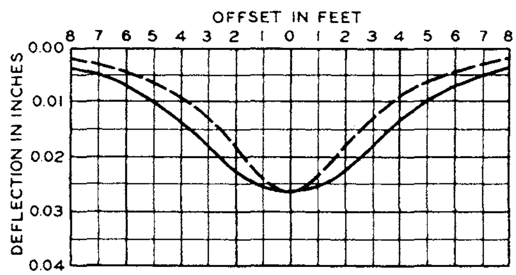
0.5-FOOT DEPTH



1.0-FOOT DEPTH



2.0-FOOT DEPTH

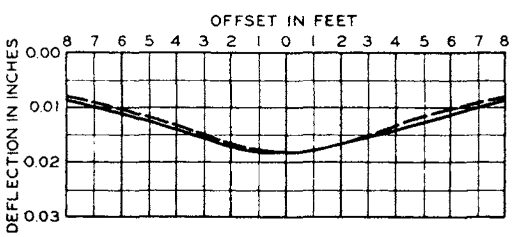


3.0-FOOT DEPTH

LEGEND

——— DUAL LOAD DEFLECTIONS

– – – SINGLE LOAD DEFLECTIONS



6.0-FOOT DEPTH

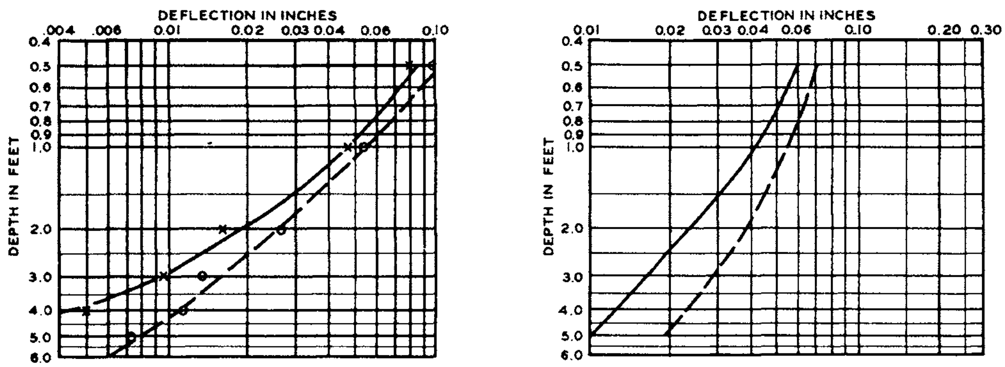
NOTE: 250-SQ-IN. PLATE, 3.0-FT DUAL SPACING
SINGLE LOAD DEFLECTIONS WERE INCREASED BY RATIO TO MAKE MAXIMUM DEFLECTIONS FOR SINGLE AND DUAL LOADINGS EQUAL.
POISSON'S RATIO = 0.3
MODULUS OF ELASTICITY = 18,000 PSI.
SURFACE LOAD = 100 PSI.

COMPARISON OF SINGLE AND DUAL DEFLECTION PROFILES

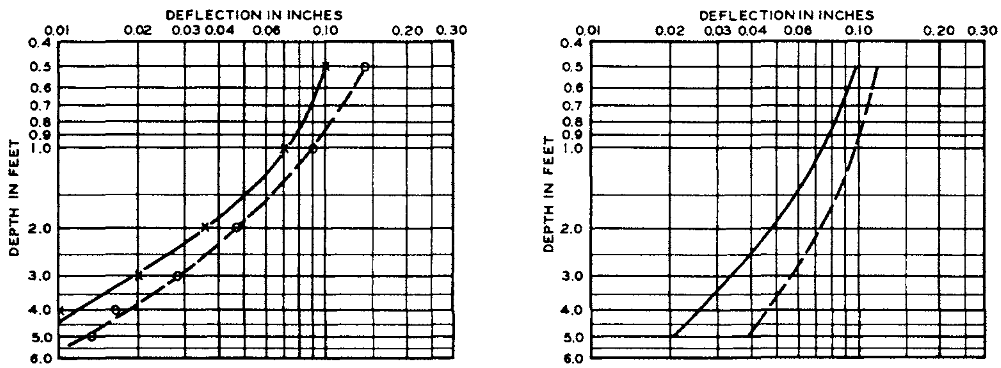
THEORY

082753A

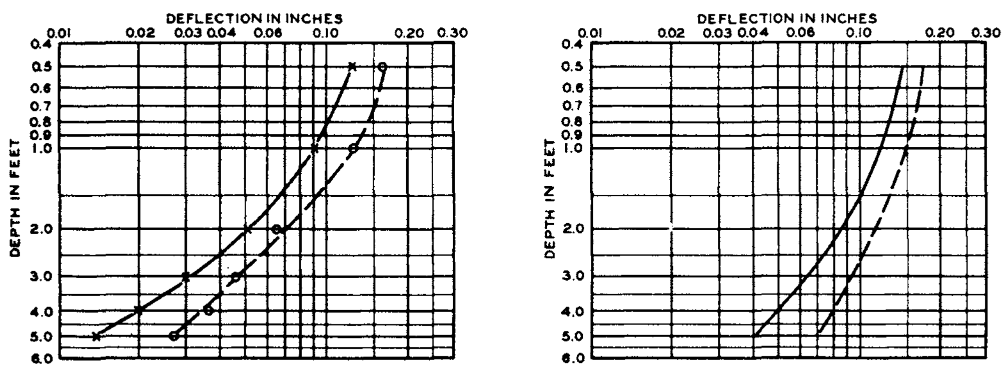
TEST DATA THEORY



250-SQ-IN. PLATE - DUAL SPACING 2.5 FT



500-SQ-IN. PLATE - DUAL SPACING 3.0 FT



1000-SQ-IN. PLATE - DUAL SPACING 4.5 FT

LEGEND

x——x SINGLE
o- - -o DUAL

NOTE: THEORY

POISSON'S RATIO = 0.3
MODULUS OF ELASTICITY = 20,000 PSI
SURFACE LOADING = 100 PSI

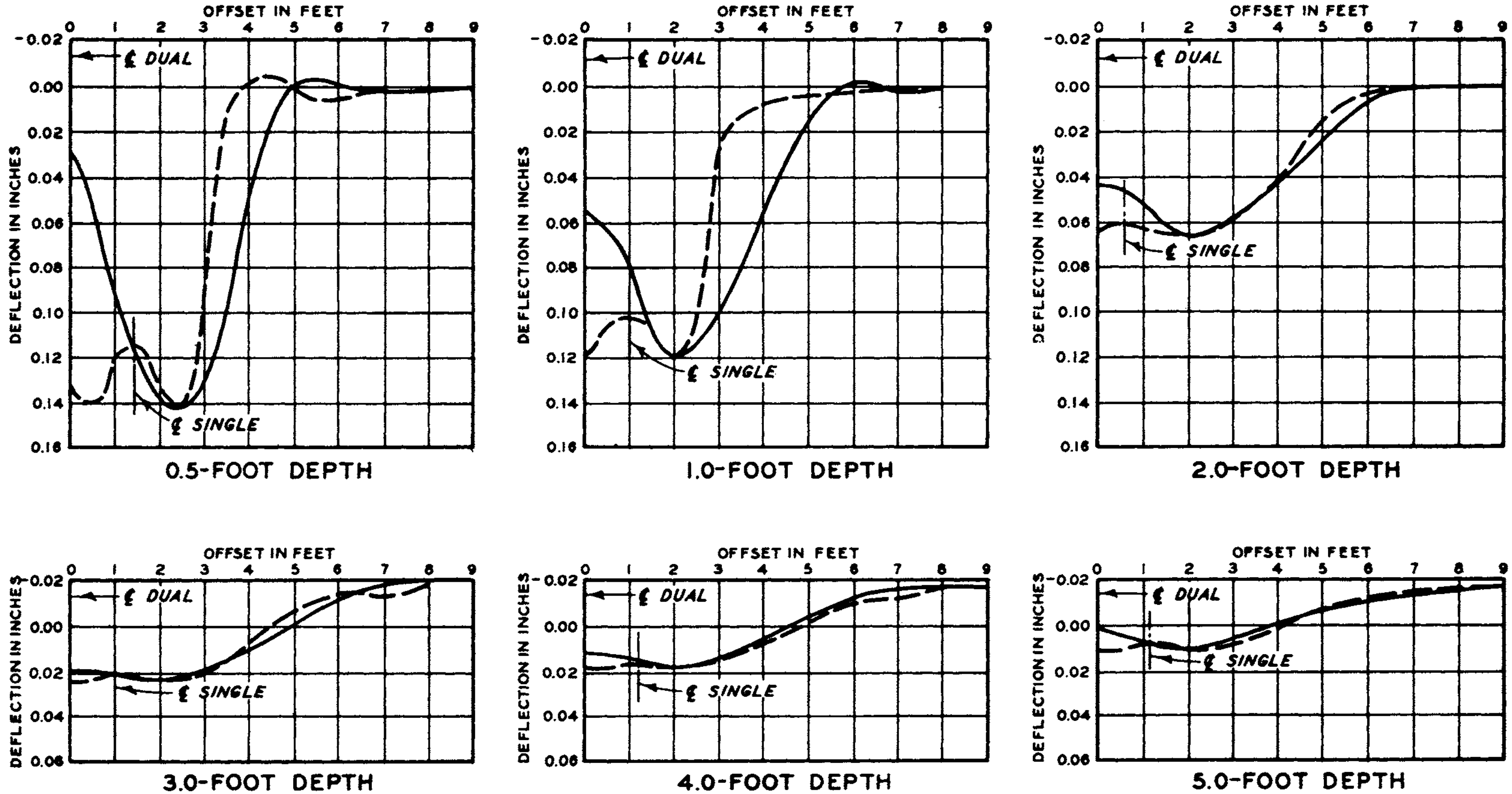
TEST DATA

HOMOGENEOUS SAND TEST SECTION
SURFACE LOADING = 100 PSI

SINGLE AND DUAL LOAD DEFLECTIONS

UNIFORM CIRCULAR LOAD

082753 G



NOTE: 1000-SQ-IN. PLATE, 4.5-FT DUAL SPACING.
SINGLE LOAD DEFLECTIONS WERE INCREASED BY RATIO TO MAKE MAXIMUM DEFLECTIONS FOR SINGLE AND DUAL LOADINGS EQUAL.
DEFLECTIONS WERE AVERAGED FROM THOSE PRODUCED BY 15-, 30- AND 60-PSI LOADINGS.

LEGEND

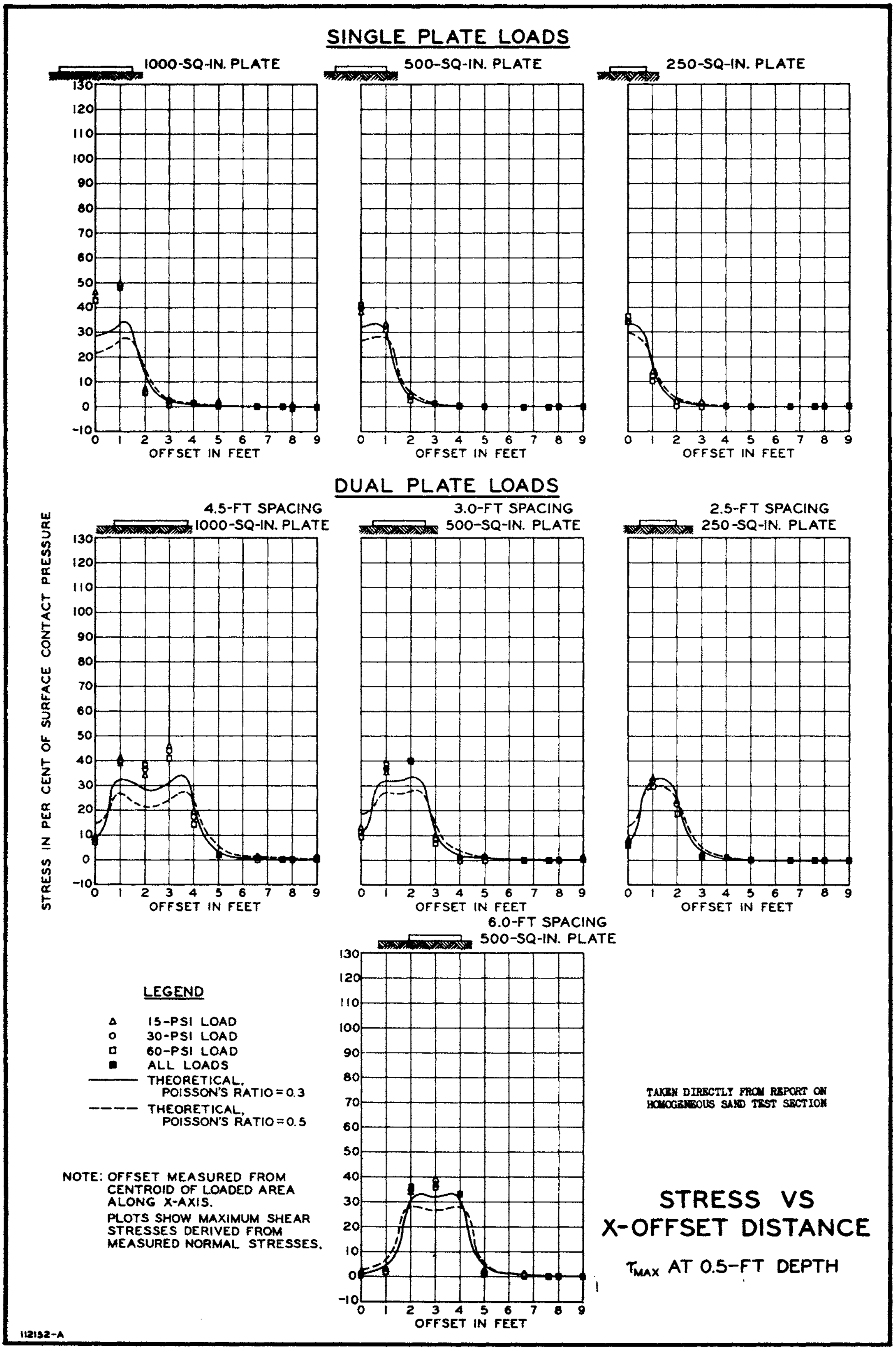
——— DUAL LOAD DEFLECTIONS
— — — SINGLE LOAD DEFLECTIONS

COMPARISON OF SINGLE AND DUAL DEFLECTION PROFILES

TEST DATA

SAND TEST SECTION

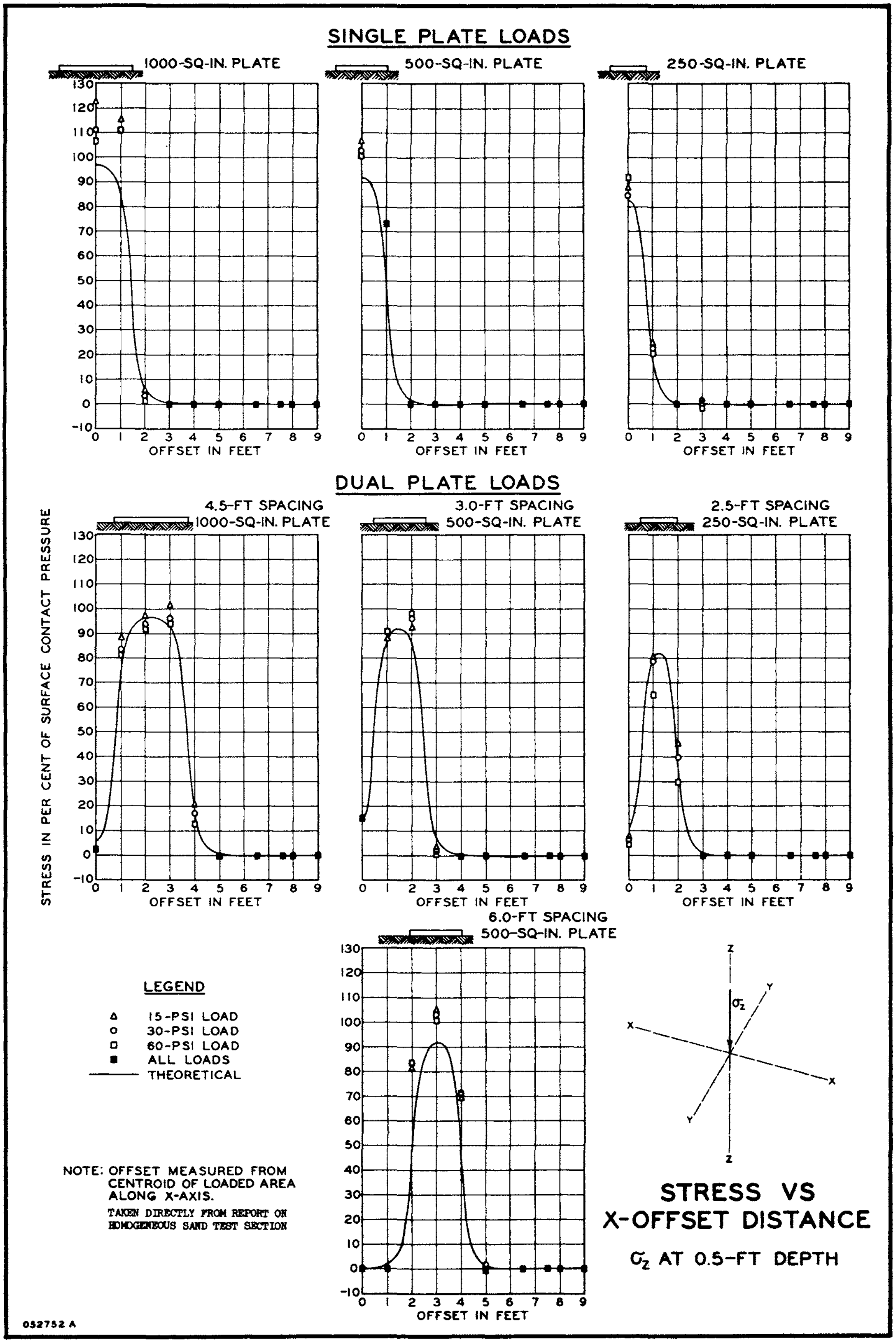
082753 B

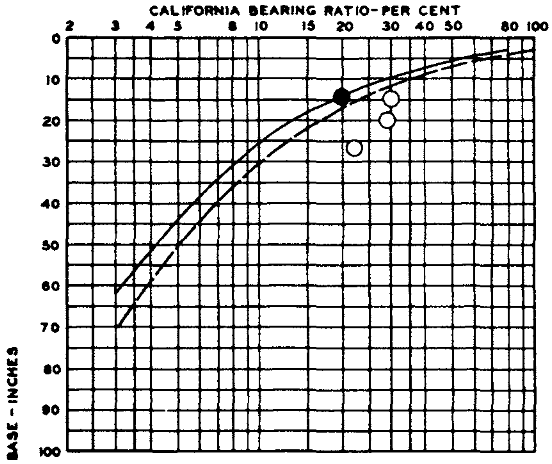


STRESS VS X-OFFSET DISTANCE

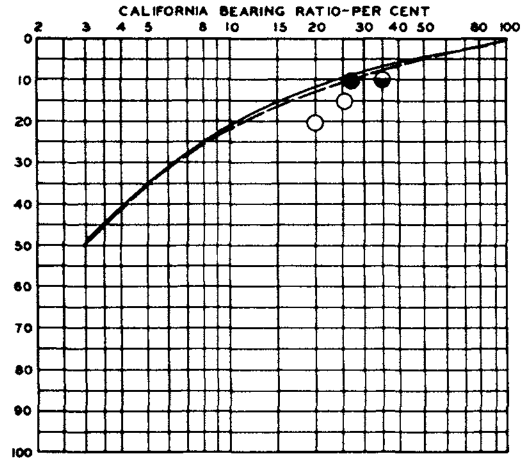
τ_{MAX} AT 0.5-FT DEPTH

PLATE 12

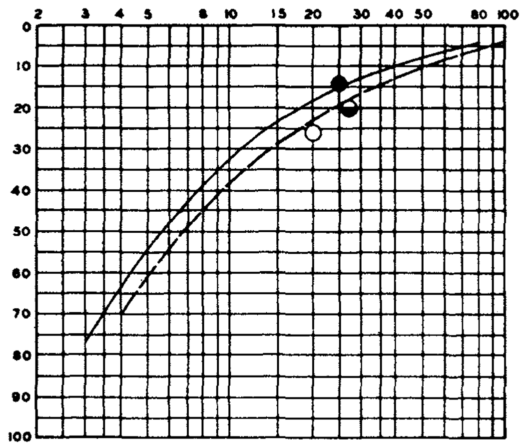

SINGLE PLATE LOADS
1000-SQ-IN. PLATE
500-SQ-IN. PLATE
250-SQ-IN. PLATE
OFFSET IN FEET
DUAL PLATE LOADS
4.5-FT SPACING
1000-SQ-IN. PLATE
3.0-FT SPACING
500-SQ-IN. PLATE
2.5-FT SPACING
250-SQ-IN. PLATE
STRESS IN PER CENT OF SURFACE CONTACT PRESSURE
6.0-FT SPACING
500-SQ-IN. PLATE
LEGEND
15-PSI LOAD
30-PSI LOAD
60-PSI LOAD
ALL LOADS
THEORETICAL
NOTE: OFFSET MEASURED FROM CENTROID OF LOADED AREA ALONG X-AXIS.
TAKEN DIRECTLY FROM REPORT ON HOMOGENEOUS SAND TEST SECTION
052752 A
STRESS VS X-OFFSET DISTANCE
σ_z AT 0.5-FT DEPTH



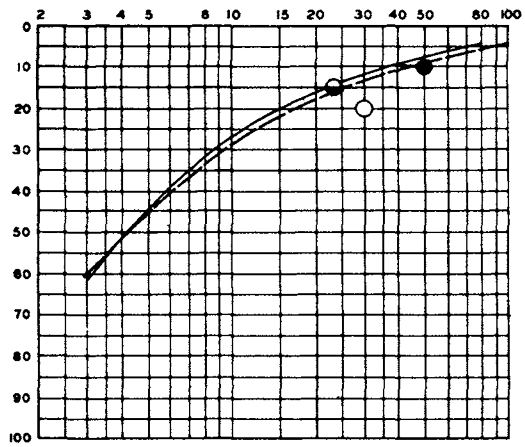
B-36 ASSEMBLY LOAD OF 150,000 LB



B-29 ASSEMBLY LOAD OF 70,000 LB



B-36 ASSEMBLY LOAD OF 200,000 LB



B-50 ASSEMBLY LOAD OF 100,000 LB

LEGEND

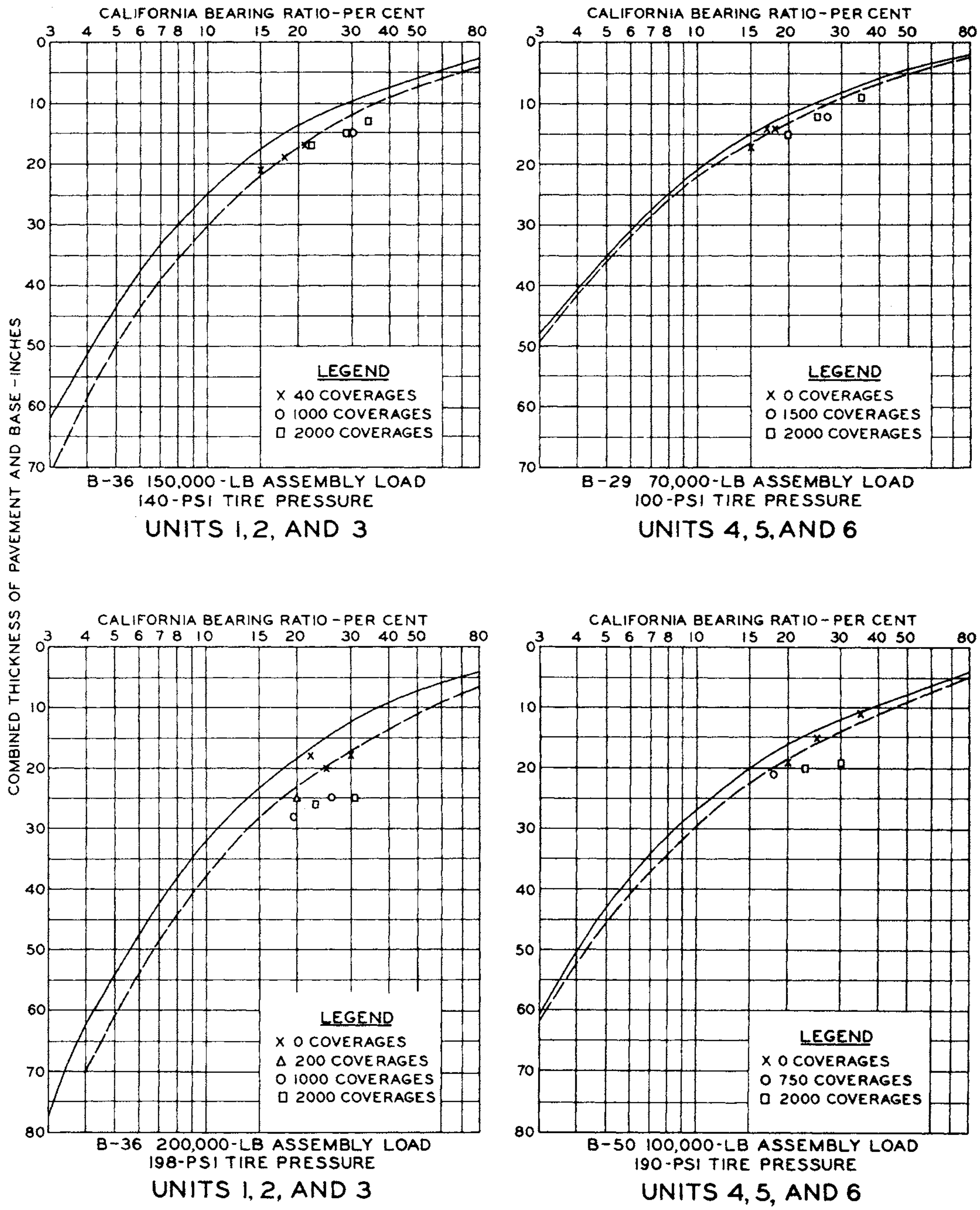
- ● INADEQUATE
- ◒ BORDERLINE
- ○ ADEQUATE

NOTE: SOLID CURVES INDICATE PRESENT DESIGN CRITERIA; DASHED CURVES INDICATE PROPOSED DESIGN CRITERIA. POINTS INDICATE PAVEMENT BEHAVIOR.

PLATE 17, MULTIPLE WHEEL REPORT NO. 1, MODIFIED TO SHOW PROPOSED DESIGN CURVES

DESIGN THICKNESSES BASED ON VISUAL OBSERVATIONS

090953A



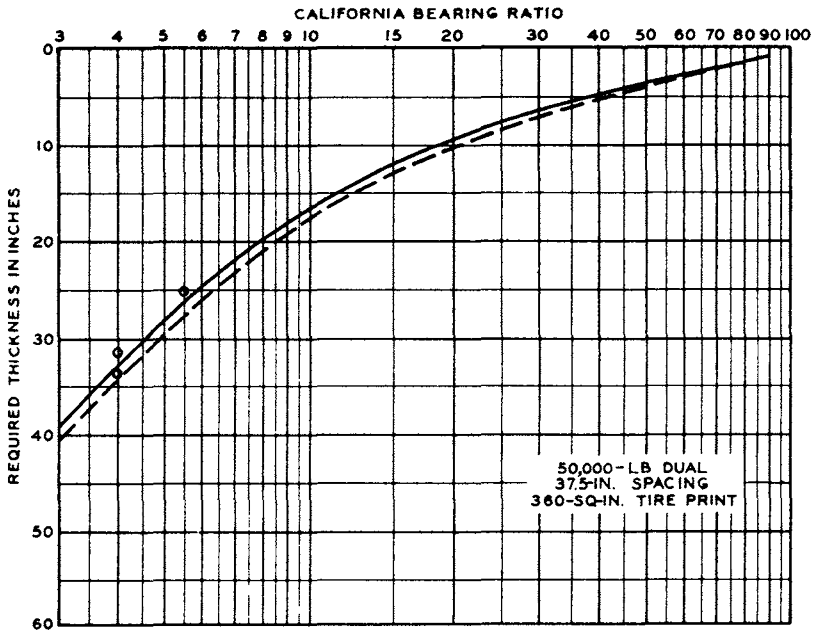
NOTE: SOLID CURVES INDICATE PRESENT DESIGN CRITERIA; DASHED CURVES INDICATE PROPOSED DESIGN CRITERIA. POINTS INDICATE THICKNESS REQUIRED FOR EQUIVALENT SINGLE-WHEEL LOAD, COMPUTED BY EQUATING DEFLECTIONS BENEATH SINGLE AND MULTIPLE LOADS.

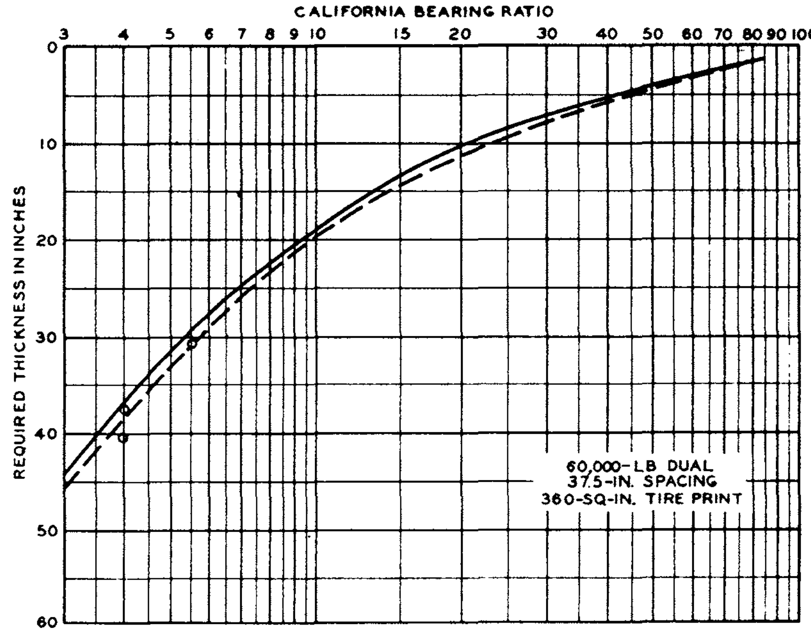
PLATE 21, MULTIPLE WHEEL REPORT NO. 1, MODIFIED TO SHOW PROPOSED DESIGN CURVES

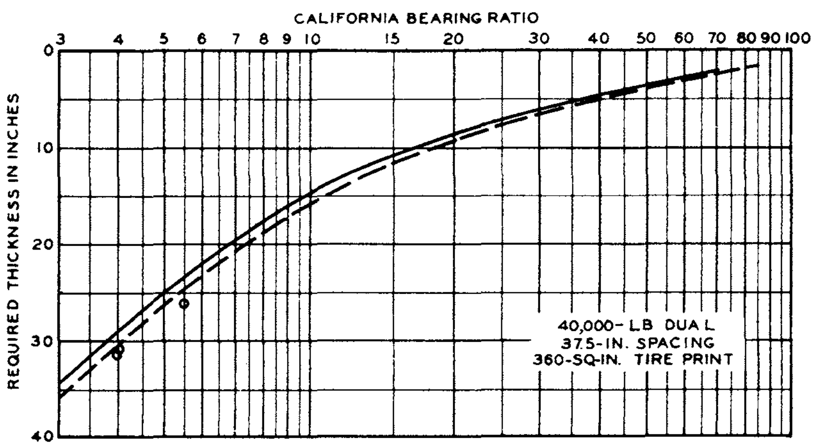
DESIGN THICKNESSES BASED ON EQUIVALENT SINGLE-WHEEL LOADS

0909538

PLATE 16







LEGEND

——— CURVES BASED ON CURRENT CRITERION

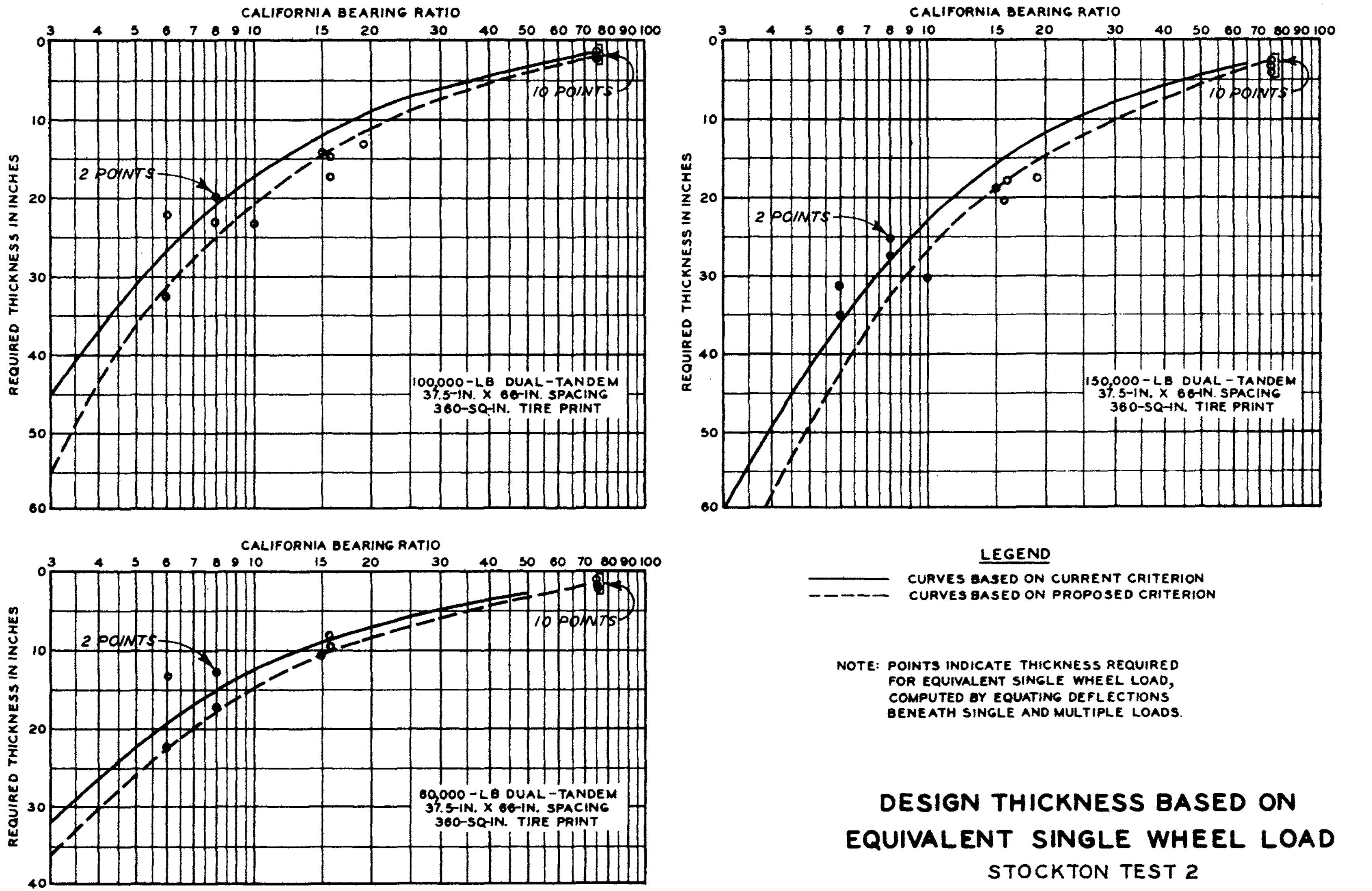
– – – CURVES BASED ON PROPOSED CRITERION

NOTE: POINTS INDICATE THICKNESS REQUIRED FOR EQUIVALENT SINGLE-WHEEL LOAD, COMPUTED BY EQUATING DEFLECTIONS BENEATH SINGLE AND MULTIPLE LOADS.

DESIGN THICKNESS BASED ON EQUIVALENT SINGLE-WHEEL LOAD

MARIETTA

082753K



LEGEND

——— CURVES BASED ON CURRENT CRITERION

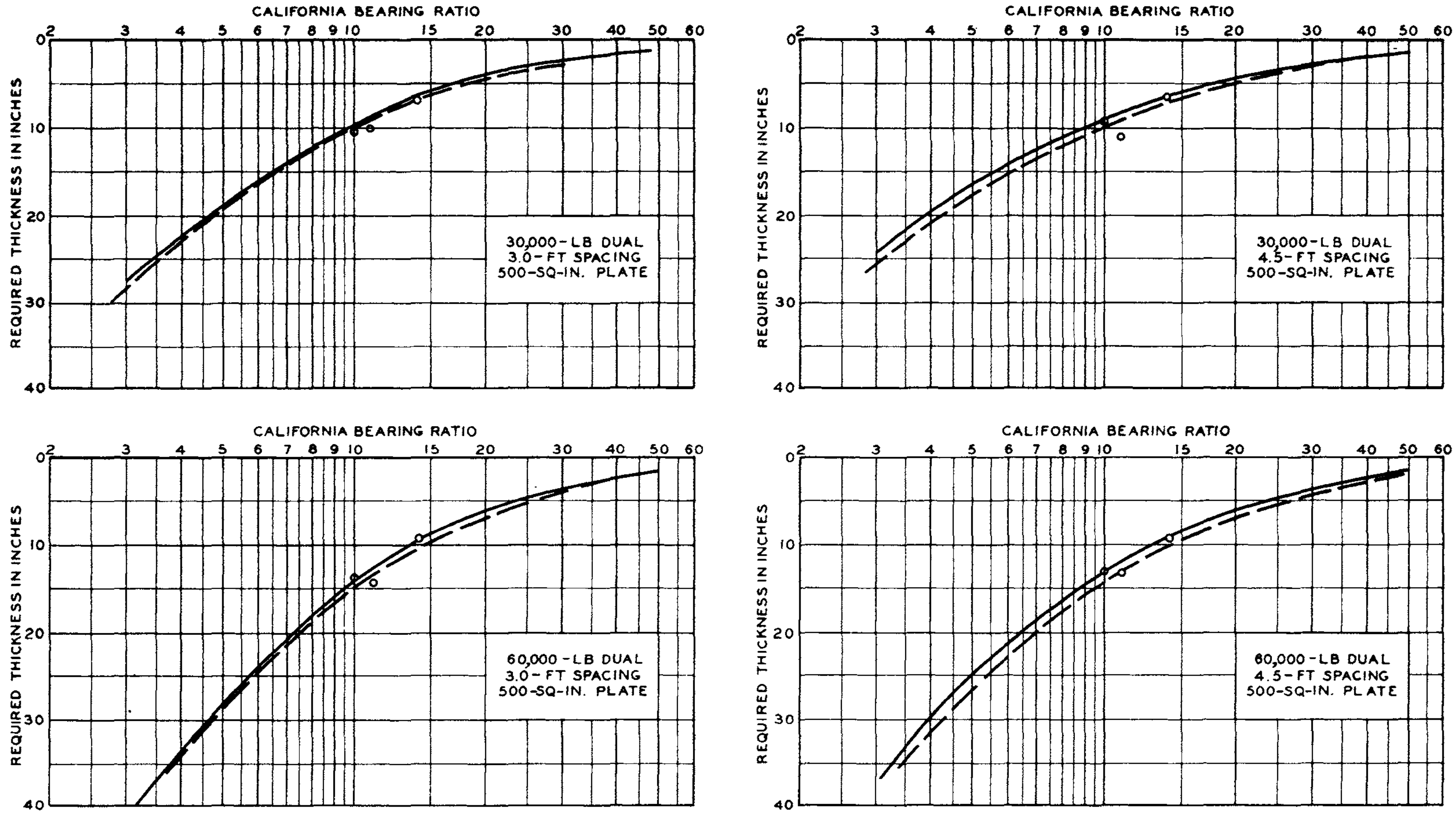
– – – – CURVES BASED ON PROPOSED CRITERION

NOTE: POINTS INDICATE THICKNESS REQUIRED FOR EQUIVALENT SINGLE WHEEL LOAD, COMPUTED BY EQUATING DEFLECTIONS BENEATH SINGLE AND MULTIPLE LOADS.

DESIGN THICKNESS BASED ON EQUIVALENT SINGLE WHEEL LOAD

STOCKTON TEST 2

082753J



NOTE: POINTS INDICATE THICKNESS REQUIRED FOR EQUIVALENT SINGLE-WHEEL LOAD, COMPUTED BY EQUATING DEFLECTIONS BENEATH SINGLE AND MULTIPLE LOADS

LEGEND

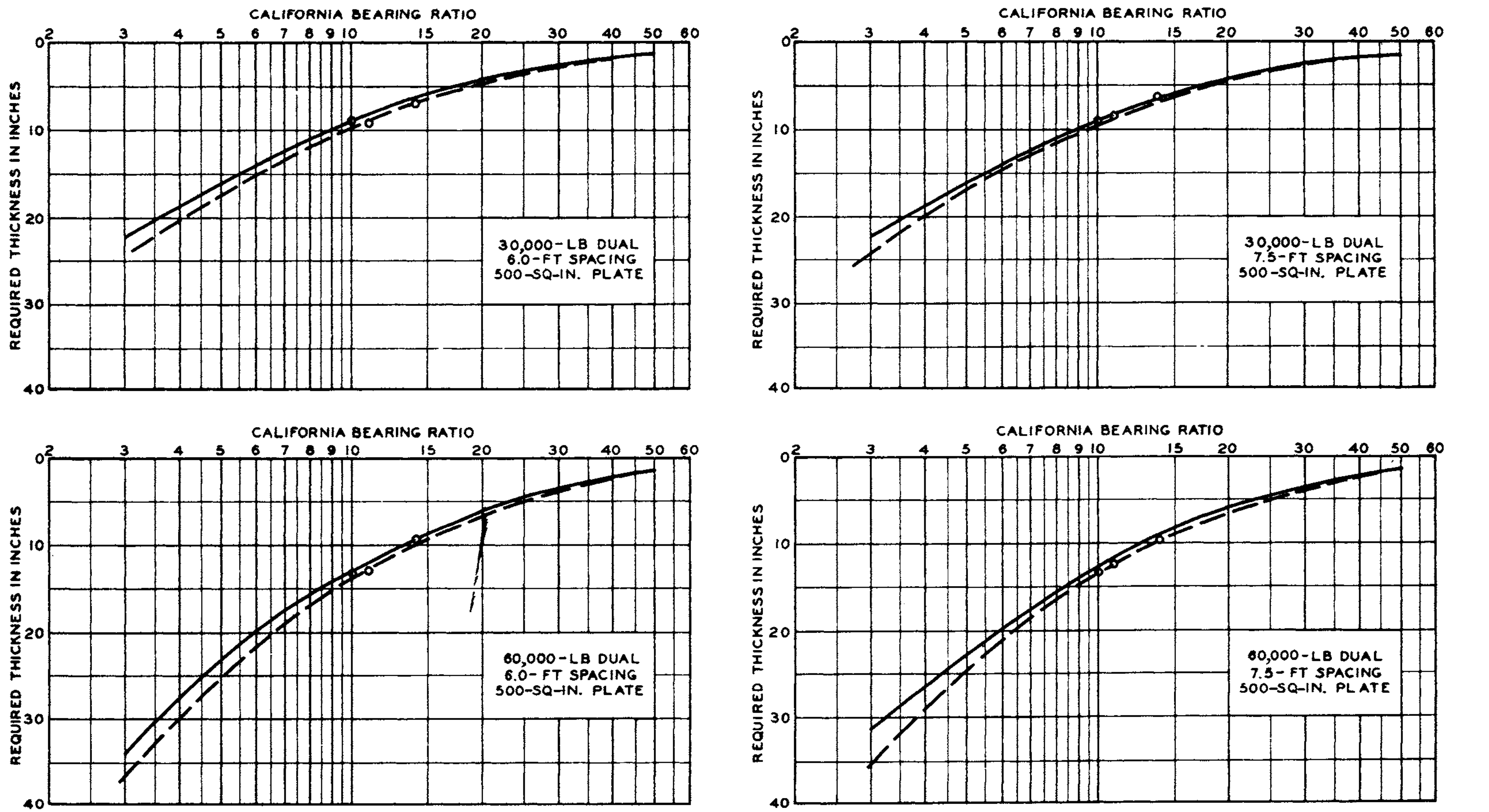
——— CURVES BASED ON CURRENT CRITERION

– – – – CURVES BASED ON PROPOSED CRITERION

DESIGN THICKNESS BASED ON EQUIVALENT SINGLE-WHEEL LOAD

HOMOGENEOUS CLAYEY-SILT TEST SECTION 3.0- AND 4.5-FT SPACINGS

082753L



NOTE: POINTS INDICATE THICKNESS REQUIRED FOR EQUIVALENT SINGLE-WHEEL LOAD, COMPUTED BY EQUATING DEFLECTIONS BENEATH SINGLE AND MULTIPLE LOADS

LEGEND

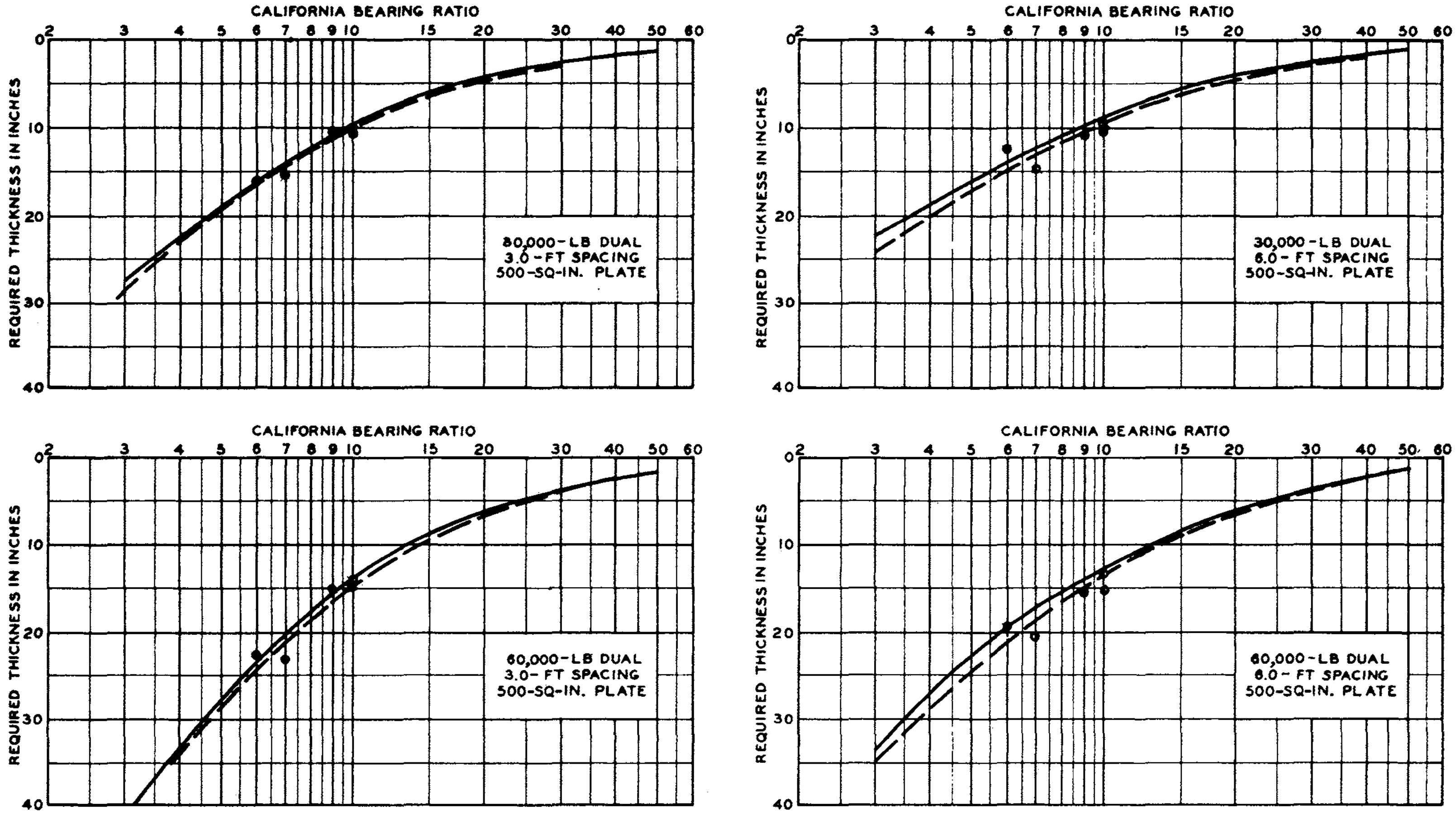
——— CURVES BASED ON CURRENT CRITERION

– – – – CURVES BASED ON PROPOSED CRITERION

DESIGN THICKNESS BASED ON EQUIVALENT SINGLE-WHEEL LOAD

HOMOGENEOUS CLAYEY-SILT TEST SECTION 6.0- AND 7.5-FT SPACINGS

082753 M



NOTE: POINTS INDICATE THICKNESS REQUIRED FOR EQUIVALENT SINGLE-WHEEL LOAD, COMPUTED BY EQUATING DEFLECTIONS BENEATH SINGLE AND MULTIPLE LOADS

LEGEND

——— CURVES BASED ON CURRENT CRITERION

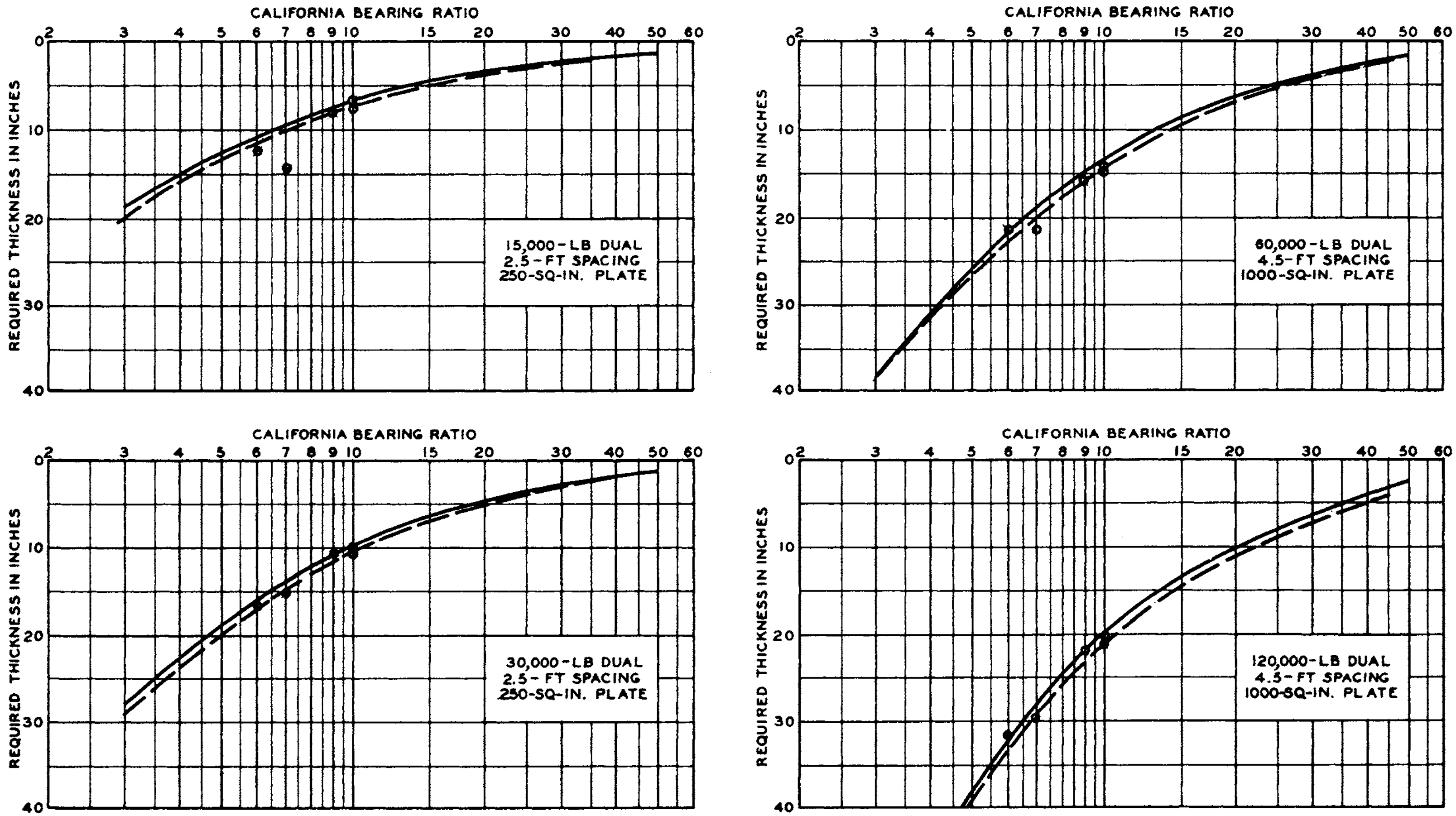
– – – CURVES BASED ON PROPOSED CRITERION

DESIGN THICKNESS BASED ON EQUIVALENT SINGLE-WHEEL LOAD

HOMOGENEOUS SAND TEST SECTION

500- SQ-IN. PLATE

082753P



NOTE: POINTS INDICATE THICKNESS REQUIRED FOR EQUIVALENT SINGLE-WHEEL LOAD, COMPUTED BY EQUATING DEFLECTIONS BENEATH SINGLE AND MULTIPLE LOADS

LEGEND

——— CURVES BASED ON CURRENT CRITERION

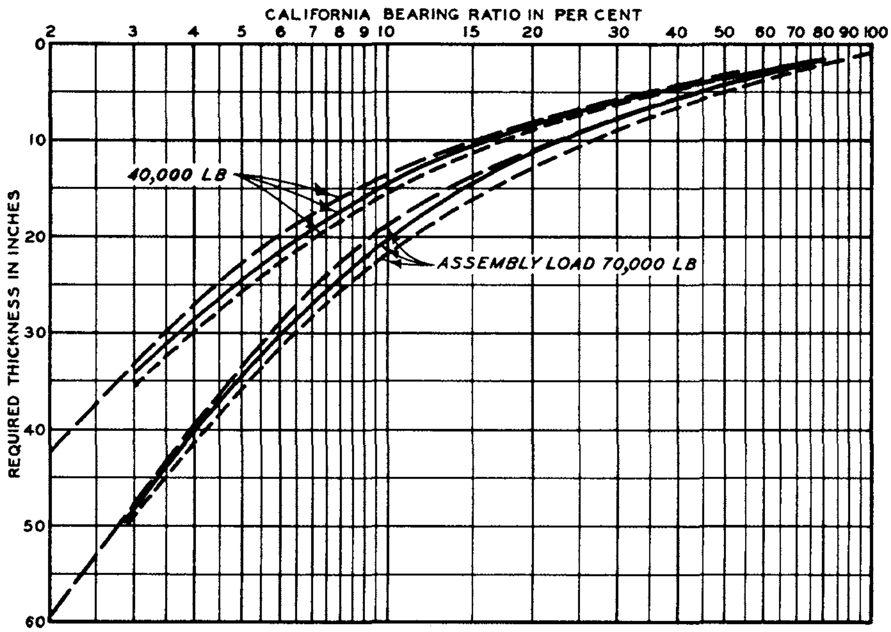
– – – – CURVES BASED ON PROPOSED CRITERION

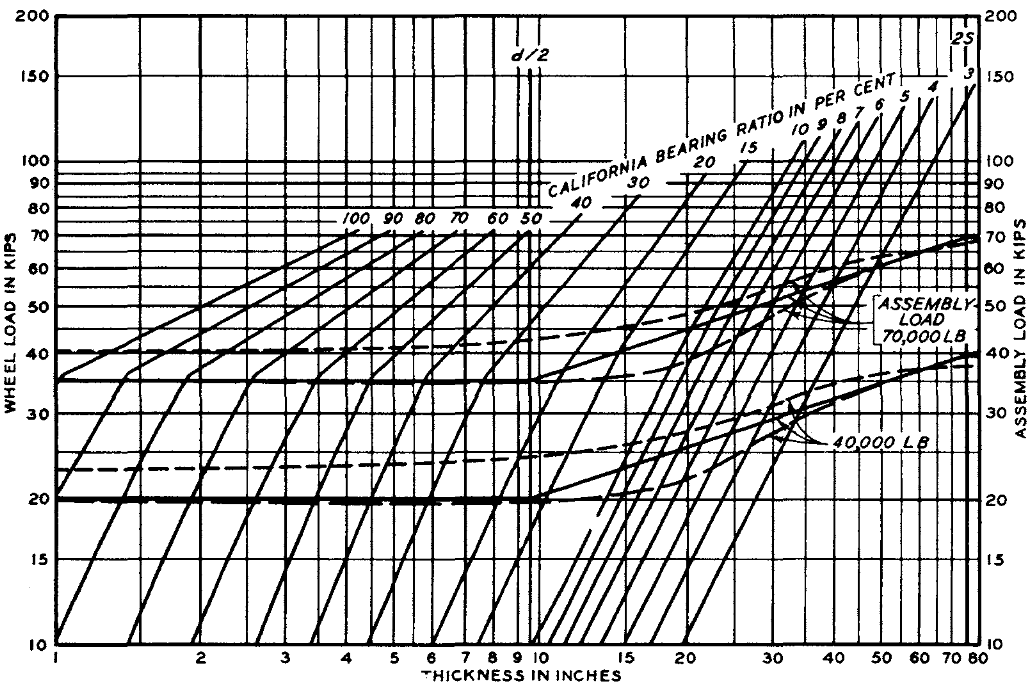
DESIGN THICKNESS BASED ON EQUIVALENT SINGLE-WHEEL LOAD

HOMOGENEOUS SAND TEST SECTION

250- AND 1000- SQ-IN. PLATES

082753N





LEGEND

- CURRENT (d/2 AND 2S) CRITERION
- CRITERION BASED ON MAXIMUM SHEAR RATIO
- PROPOSED CRITERION BASED ON MAXIMUM DEFLECTION RATIO

COMPARISON OF DESIGN CRITERIA

B-29

360-SQ-IN. TIRE PRINT

DUAL SPACING 37.5 IN. C-C

082753F

APPENDIX A: EXAMPLE OF THE COMPUTATION OF EQUIVALENT SINGLE WHEEL LOAD

1. This appendix provides a detailed example of the method by which theoretical maximum deflections are developed for single- and multiple-wheel assemblies and combined to give a relation between multiple- and equivalent single-wheel loads.

Assume: A dual assembly, 40-in. c-c spacing, 314-sq-in. contact area, A, each wheel.

Then:

$$\text{radius, } r = \sqrt{\frac{A}{\pi}} = \sqrt{\frac{314}{\pi}} = 10\text{-in.}$$

$$\text{spacing in radii} = \frac{40}{10} = 4 \text{ radii between duals.}$$

Plate A1, which is taken from reference (5) (see main report), gives deflections for a single load in terms of deflection factor, F, such that:

$$\text{Deflection, } \omega = \frac{prF}{E_m}$$

where

p = load intensity,

E_m = modulus of elasticity.

The following tabulation of deflection factors is taken directly from plate A1:

Table A1

Depth in.	Deflection Factors Offset from Center of Single Load: Beneath Center	2 Radii or 20 in.	4 Radii or 40 in.
0	1.50	0.39	0.19
r or 10	1.06	0.41	0.20
2r or 20	0.67	0.38	0.20
3r or 30	0.47	0.34	0.20
4r or 40	0.36	0.29	0.20
5r or 50	0.29	0.25	0.19
6r or 60	0.25	0.22	0.17

2. By the principle of superposition, the deflection beneath one wheel of the dual loading is equal to that beneath the center of a single load plus that at 40 in. (4 radii) offset. Also, deflection beneath the center of the dual assembly is twice that at 20 in. (2 radii) offset beneath the single. Thus, by adding the outer columns from the table on the preceding page and by doubling the center column, we arrive at the following table of deflection factors:

Table A2

Depth in.	Deflection Factors: Beneath One Wheel of Dual	Deflection Factors: Beneath Center of Dual
0	1.69	0.78
10	1.26	0.82
20	0.87	0.76
30	0.67	0.68
40	0.56	0.58
50	0.48	0.50
60	0.42	0.44

3. The maximum deflection beneath one wheel of the dual represents the maximum deflection anywhere beneath the dual loading for shallow depths. Similarly, the maximum deflection midway between the dual wheels represents the maximum deflection anywhere beneath the dual loading for deep depths. The maximum deflection beneath the dual wheels in the transition zone is most easily determined by plotting curves from the data in table A2 on a single plot and visually adding a limiting, or transition, curve. It could be determined more exactly by superposing deflections beneath the individual wheels of the duals for all offsets between the wheels and selecting the maximum, but the added accuracy does not justify the increased effort. Table A1 lists deflection factors beneath the center of a single-wheel load. These are the maximum deflection factors for a single load. Plate A2 gives maximum deflection factors for the dual load.

4. The load on a single wheel of the same contact area as one wheel of the dual assembly that produces a maximum deflection equal to

that beneath the dual assembly is assumed to be equivalent to the dual loading (refer to part IV of the main report). We may, therefore, equate deflections from table A1 and plate A2. These are expressed as deflection factors such that $\omega = \frac{prF}{E_m}$. By using subscripts s and d to denote single and dual, we may write:

$$\omega_s = \frac{r_s}{E_m} p_s F_s \text{ and } \omega_d = \frac{r_d}{E_m} p_d F_d$$

And since ω_s is to equal ω_d, and r_s is to equal r_d (this is true since A_s is to equal A_d),

$$p_s F_s = p_d F_d \text{ or } \frac{p_s}{p_d} = \frac{F_d}{F_s}$$

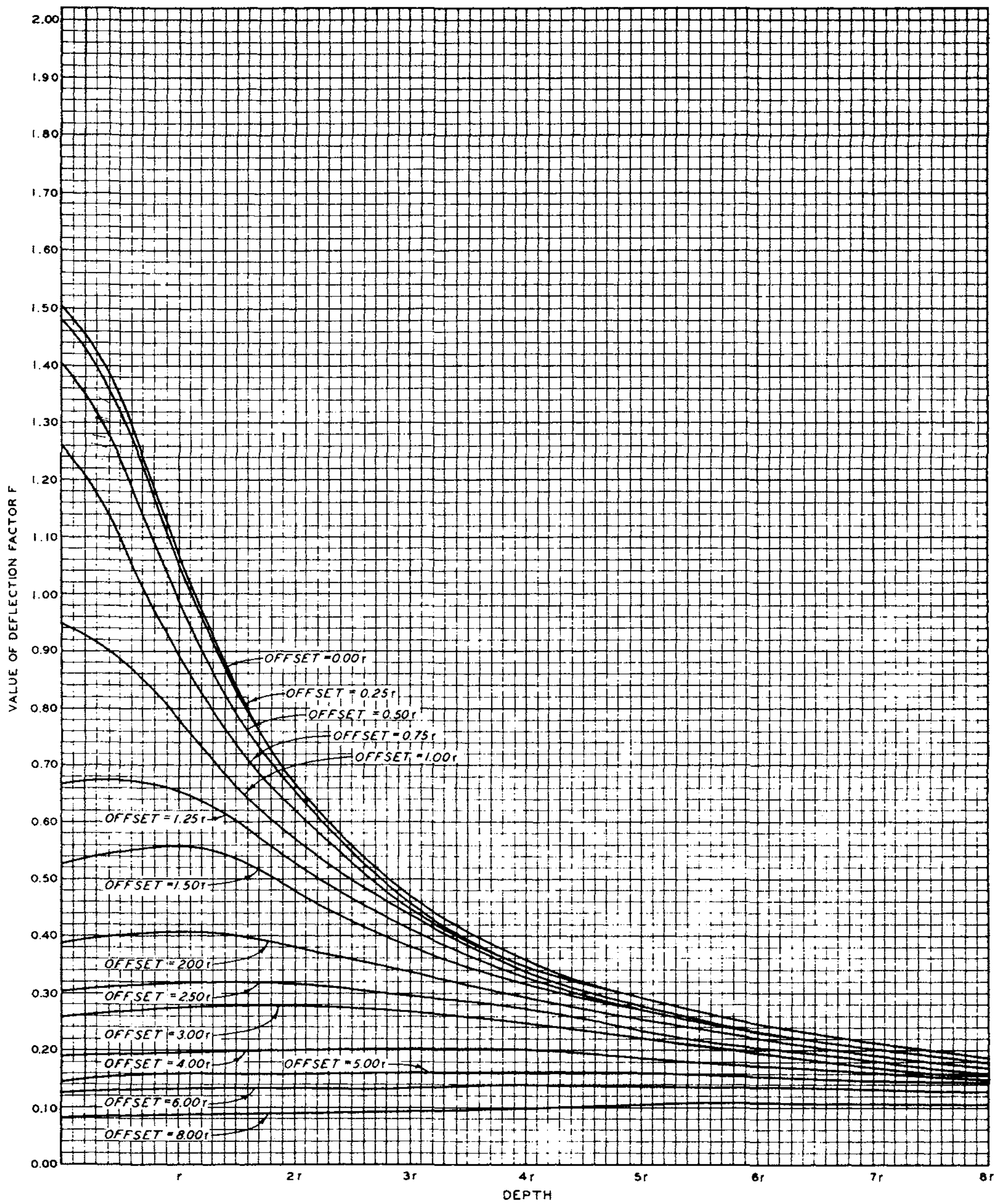
Since contact area is the same for both single and dual, the ratio of total load must be the same as that for unit pressure. Therefore $\frac{P_s}{P_d} = \frac{F_d}{F_s}$. Thus, the ratio of the equivalent single-wheel load to the load on one wheel of the dual assembly is the inverse of the ratio of the maximum deflection factors. In the following table the ratios of dual- and equivalent single-wheel loads are determined for the various depths:

Table A3

Depth in.	Single-wheel Deflection Factor	Dual-wheel Deflection Factor	Load Ratio: Single-to-one Wheel of Dual	Load Ratio: Single-to-dual Assembly
0	1.50	1.69	1.13	0.565
10	1.06	1.27	1.20	0.600
20	0.67	0.89	1.33	0.665
30	0.47	0.70	1.49	0.745
40	0.36	0.58	1.61	0.805
50	0.29	0.50	1.72	0.860
60	0.25	0.44	1.76	0.880

The ratios listed in the right-hand columns of table A3 can be applied directly to the load on the dual assembly (or on one wheel of the assembly) to determine the equivalent single-wheel load for the assembly for the pertinent depth. For example, assume that the dual assembly is loaded with 50 kip and we are concerned with a depth of 20 in.: From table A3 the ratio of single- to dual-assembly loads is 0.665; therefore, the equivalent single-wheel load is 50 x 0.665 = 33.3 kip. Or, we may use the load on one wheel of the dual which is 25 kip. From table A3 the ratio of single load to the load on one wheel of the dual is 1.33. The equivalent single-wheel load is, therefore, 25 x 1.33 = 33.3 kip. The ratios used to relate the 50-kip dual to its equivalent, 33.3-kip, single-wheel load, are valid for all loadings on this dual assembly. Thus, the equivalent single-wheel load for the 20-in. depth for any load can be established.

5. From the 33.3-kip equivalent single-wheel load and the single-wheel CBR curves, the CBR required at a depth of 20 in. to support the 50-kip dual-wheel load can be determined. For the 100-psi-tire-pressure CBR curves this CBR would be 8.2, and in the same way the CBR values for other loads can be established. By repeating this procedure for various depths, the relation between CBR, thickness of pavement and base, and load can be established and curves drawn for the dual loading selected as an example. This operation can then be repeated for other dual loadings and for other configurations as well.



$\omega = \frac{prF}{E_m}$

ω = VERTICAL DEFLECTION IN INCHES

r = RADIUS OF LOADED CIRCULAR AREA IN INCHES

E_m = ELASTIC MODULUS IN PSI

F = DEFLECTION FACTOR

z = DEPTH IN INCHES

p = SURFACE CONTACT PRESSURE IN PSI

NOTE: FOR POINTS BENEATH THE CENTER OF THE CIRCULAR AREA (OFFSET = 0.0 r) $F = \frac{3r}{2\sqrt{z^2+r^2}}$

OFFSETS MEASURED FROM ORIGIN ALONG X-AXIS.

DEFLECTION FACTOR F

FOR UNIFORM CIRCULAR LOAD OF RADIUS r AT POINTS BENEATH THE X-AXIS POISSON'S RATIO = 0.5

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PLATE A2

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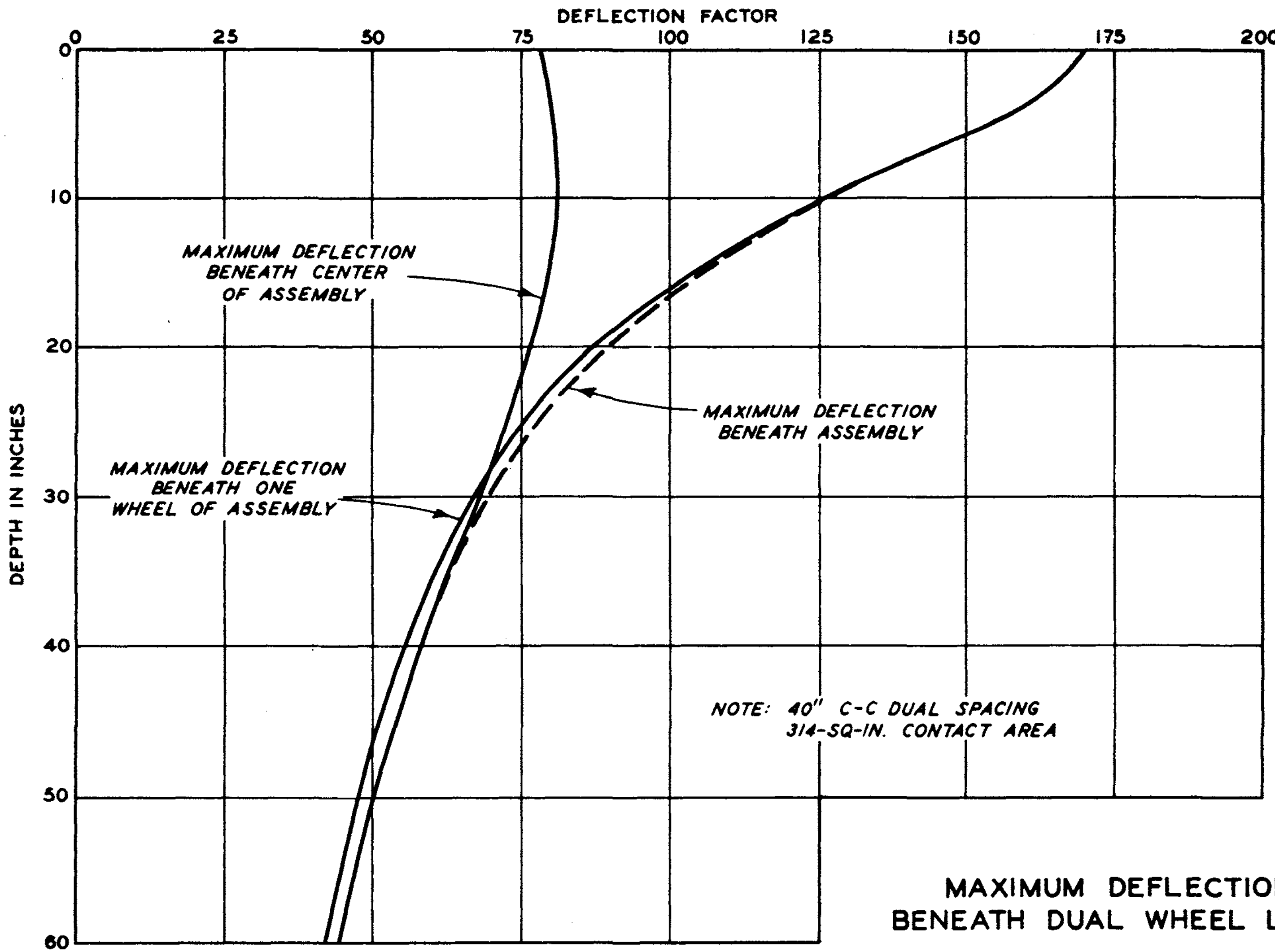

MAXIMUM DEFLECTION
BENEATH DUAL WHEEL LOAD